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Reinventing International Nuclear Safeguards in the Centrifuge Enrichment Era

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REINVENTING INTERNATIONAL NUCLEAR SAFEGUARDS IN THE CENTRIFUGE ENRICHMENT ERA

Mark Edwin Walker

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Abstract

International nuclear safeguards for gas centrifuge enrichment plants (GCEPs) are a key element of the nuclear nonproliferation regime. GCEPs, when misused, can produce material suitable for use in nuclear explosive devices on a rapid time scale, given sufficient capacity. In addition, current technical and political conditions are placing GCEP safeguards under increased scrutiny. Commercial GCEP capacities, along with their potential for rapid misuse, have grown in capacity over the past two decades as gas centrifuge technology has risen to predominance in the uranium enrichment market. Ongoing political attention has been devoted to safeguards verification at Iranian GCEP facilities. Amidst these conditions, this dissertation assesses measures that can be taken to ensure the continual effectiveness and efficiency of international safeguards at GCEPs.

In making this assessment, this dissertation studies how safeguards inspectorates, technology holder States and facility operators addressed GCEP safeguards in the past. To date, however, the origins and developmental history of GCEP safeguards have not been thoroughly studied in published literature. This dissertation analyzes an extensive history of GCEP safeguards gathered through archival research in the United States, the United Kingdom, and Germany to inform recommendations on what should be done to improve GCEP safeguards today.

Historical evidence shows that early GCEP safeguards development efforts were beset by a variety of political disputes. These disagreements largely pertained to the negotiation of measures for verifying the absence of GCEP misuse to produce highly enriched uranium (HEU) as weapons material. As a result, international safeguards measures addressing this activity were formed

primarily as products of political compromise, with technical considerations playing only a background role. These measures originally provided a substantial deterrent to HEU production. Since the early 1980s, however, when these measures were agreed, the ability of safeguards inspectorates to detect this activity in a timely manner has diminished, leading to a current gap between safeguards needs and capabilities. Based on this research, this dissertation proposes applications of novel unattended monitoring technology to improve detection timeliness capabilities for HEU production and suggests next steps for implementing these systems in the politically charged environment that characterizes contemporary international safeguards discourse.

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List of Acronyms

AA	[FRG] Foreign Office (Auswärtiges Amt)
ABACC	Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials
AEM	Advanced Enrichment Monitor
BMBW	[FRG] Federal Ministry for Education and Science (Bundesministerium für Bildung und Wissenschaft)
BMFT	[FRG] Federal Ministry for Research and Technology (Bundesministerium für Forschung und Technologie)
BNFL	British Nuclear Fuels Limited
BoG	[IAEA] Board of Governors
CCD	[United Nations] Conference of the Committee on Disarmament
CHEM	Cascade Header Enrichment Monitor
CEMO	Continuous Enrichment Monitor
C/S	Containment and Surveillance
CSA	Comprehensive Safeguards Agreement
DDG	Deputy Director General
DG	Director General
DIV	Design Information Verification
DTI	[UK] Department of Trade and Industry
ES	Environmental Sampling
Euratom	European Atomic Energy Community
FA	Facility Attachment
FRG	Federal Republic of Germany

F/W	Feed and Withdrawal
GCEP	Gas Centrifuge Enrichment Plant
GUZ	Gas Ultracentrifuge (Gasultrazentrifuge)
HEU	Highly Enriched Uranium
HSP	Hexapartite Safeguards Project
IAEA	International Atomic Energy Agency
INFCIRC	Information Circular
JC	[Tripartite] Joint Committee
JCPOA	Joint Comprehensive Plan of Action
KMP	Key Measurement Point
LCM	Load Cell Monitoring
LEU	Low Enriched Uranium
LFUA	Limited Frequency Unannounced Access
MBA	Material Balance Area
MIST	Minor Isotope Safeguards Technique
MRIE	Maximum Routine Inspection Effort
NDA	Non-Destructive Assay (also Non-Destructive Analysis)
NPT	Treaty on the Nonproliferation of Nuclear Weapons
NWS	Nuclear Weapon State
NNWS	Non-Nuclear Weapon State
OLEM	Online Enrichment Monitor
PIV	Physical Inventory Verification
SCWG	Security and Classification Working Group (of the Tripartite JC)

SOS	Subcommittee on Safeguards (of the Tripartite JC)
SSAC	State System of Accounting for and Control of Nuclear Material
SWU	Separative Work Unit (1 tSWU = 1000 kgSWU)
TSWG	Troika Safeguards Working Group (of Urenco)
UCN	Ultra-Centrifuge Nederland
UCVS	Unattended Cylinder Verification Station
UKAEA	United Kingdom Atomic Energy Authority
UKDOE	United Kingdom Department of Energy
UKFCO	United Kingdom Foreign & Commonwealth Office
UMS	Unattended Monitoring Systems
UNAEC	United Nations Atomic Energy Commission
UNGA	United Nations General Assembly
USAEC	United States Atomic Energy Commission
USDOE	United States Department of Energy
VOA	Voluntary Offer Agreement

Chapter 1 – Introduction

"Too technical for politicians and too political for technicians"

Nuclear nonproliferation is a challenging field not only because of the lofty goals it seeks to accomplish, but also because of its disciplinary nature. At its core, the business of preventing the spread of nuclear weapons is both deeply technical and deeply political. Implementing nuclear nonproliferation policy requires tremendous scientific capability, from the development and use of novel measurement devices to measure radiological and non-radiological signatures produced by nuclear fuel cycle materials, to the creation and refinement of computer models to aid in redesigning reactors so that they produce or use less weapons-usable material, to the development of detailed export control regulations that effectively restrict the flow of sensitive nuclear technology. Political dynamics in nonproliferation, however, are pervasive. Much of the nonproliferation regime is overseen by international authorities managed by their Member States, which often disagree over how these organizations should be run. International cooperation, nevertheless, both on a bilateral and multilateral basis, and between States and international authorities, is essential to a healthy nonproliferation system. Meanwhile, domestic politics in individual States, as well as the behavior of non-State entities, such as facility operators, are inherently intertwined with nonproliferation. Nuclear fuel cycle capabilities and nuclear weapons are powerful international and domestic political currency, as is denying the ability of another State to acquire the same capabilities. Political coordination is crucial to nonproliferation. Verification activities require coordination between inspector and host parties. A reactor fueled by

weapons-usable material cannot be reconfigured if State authorities that oversee its operation do not consent. Export control regulations, if unenforced, have little use.

The field of international safeguards, like other major components of the nuclear nonproliferation system, depends heavily on both technical prowess and political cooperation. In short, the aim of international safeguards is to assure the global community that nuclear material, both in the civil nuclear fuel cycle and in civil applications of nuclear technology, is not misappropriated for military purposes—i.e. the production of nuclear weapons. Within the civil fuel cycle, safeguards are applied on nuclear material from the conversion of uranium from ore concentrate, to the disposition of spent nuclear fuel. This task is accomplished via a system of declarations by State and regional authorities, facilitated by data from facility operators and owners of nuclear material, and verification of this information by international inspectorates. One inspectorate, the International Atomic Energy Agency (IAEA) carries out safeguards on a global scale. In addition, two regional inspectorates—the European Atomic Energy Community (Euratom) and the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC) respectively perform safeguards verification in Europe, and in Brazil and Argentina. The techniques that are used to produce declarations, as well as those used to verify them, are highly technical, from radiation measurement techniques used to quantify the amount of nuclear material in closed containers, to the statistical methods used to plan inspection activities. Nevertheless, both the IAEA and Euratom, although they are staffed by technical secretariats, are ultimately governed by Member States that possess considerable control over the means of verification, capabilities, and resources upon which these organizations can draw. To grasp the full breadth and depth of technical and political intricacies that permeate international safeguards is highly challenging.

More succinctly, the subject has been described as "too technical for politicians and too political for technicians."[1] This dissertation attempts to bridge this gap.

The Basics of Gas Centrifuge Enrichment Safeguards

This dissertation studies the application of international safeguards at uranium enrichment facilities, specifically gas centrifuge enrichment plants (GCEPs). Enrichment safeguards are a particularly critical undertaking. Along with nuclear reprocessing plants, uranium enrichment plants can be used to produce material suitable for use in a nuclear weapon without changes to its isotopic content, and free of undesirable radionuclides. Unlike nuclear reprocessing, however, which is not essential to the nuclear fuel cycle and is only carried out for civil purposes in a handful of countries, uranium enrichment is an integral part of civil nuclear power generation. The vast majority of today's power reactor fleet are of the type known as Light Water Reactors (LWRs) and require enriched uranium for fuel. The term 'light' is used here to distinguish LWRs from Heavy Water Reactors (HWRs), which rely on deuterium oxide, or heavy water, for cooling and moderating neutrons to sustain a steady nuclear fission chain.[2] LWRs make use of water, in its naturally occurring isotopic form, to perform these functions. HWRs can generally be fueled with natural uranium, which by mass consists of 0.7% ^{235}U and 99.3% ^{238}U. Of these two uranium isotopes, only ^{235}U can be readily fissioned by thermal neutrons. Because of the higher presence of ^{1}H in LWRs, which has a propensity to absorb neutrons that could otherwise cause fission, the

[1] Roger Howsley, "Transcript of Interview with Current and Former SAGSI Members: Jim Casterton, Dieter Tillwick, Roger Howsley, Kaoru Naito and Jim Tape," PNNL-SA-56894 (Pacific Northwest National Laboratory, July 13, 2007), 3.

[2] Deuterium is synonymous with the ^{2}H isotope, which must be produced artificially via separation of naturally occurring ^{2}H from the far more common ^{1}H isotope.

proportion of ^{235}U in LWR fuel must be increased, generally to between 3% and 5%. Uranium enrichment—the separation of uranium isotopes to produce a product containing a higher-than-natural concentration of ^{235}U—accomplishes this task.

While material enriched to between 3% and 5% for power generation is not suitable for in a nuclear explosive device, uranium containing higher proportions of ^{235}U can be weapons-usable. Uranium enriched from anywhere between its natural isotopic ratio to 20% is not suitable for use in a nuclear weapon, and is termed 'low enriched uranium,' or LEU. Material enriched beyond this level is designated 'highly enriched uranium' (HEU) and can theoretically be used in a nuclear weapon without further changes to its isotopic content. Higher enrichment levels than 20%, however, are necessary to build a practical, deliverable device. In general, uranium destined for use in nuclear weapons is enriched to around 90% ^{235}U or higher. The term 'weapons-grade uranium' is often used to describe this material. Material containing a higher-than-natural ^{238}U fraction, often waste material from the enrichment process known as 'tails,' is known as 'depleted uranium,' or DU.[3]

In a centrifuge enrichment plant, uranium, in the form of uranium hexafluoride (UF_6), is fed into centrifuge rotor tubes spinning at very high frequencies. Rotational forces inside a centrifuge create a radial difference in isotopic concentration levels within the rotor, with ^{235}U concentrating around the axis of the machine, and with ^{238}U higher concentration levels towards the rotor wall. This effect can be greatly amplified by inducing an axial countercurrent flow of UF_6 inside a rotor,

[3] International Atomic Energy Agency, *IAEA Safeguards Glossary, 2001 Edition*, International Nuclear Verification Series No. 3 (Vienna: International Atomic Energy Agency, 2002), 31–32.

which causes an isotopic concentration gradient to form along its axis.[4] Two streams of UF_6 are withdrawn from a centrifuge: a product stream slightly enriched in ^{235}U relative to the machine's feed, and a tails stream slightly depleted in ^{235}U. Because this difference between the product and feed enrichments of a single centrifuge is incremental, and because the throughput capacity of a single centrifuge is small, centrifuges must be piped together both in series and parallel to form a 'cascade.' In general, connecting centrifuges in series increases the product enrichment level, and adding machines in parallel will increase the capacity of the cascade. Centrifuges that are connected in parallel form 'stages.' The product line from a given stage *s* is used to feed the stage immediately above it (*s+1*), in combination with the tails line from stage *s+2*.

Although essentially all global enrichment demand is satisfied by GCEPs today, gas centrifuge technology was not used beyond laboratory-scale experiments outside the Soviet Union until the 1970s. In the early days of nuclear fuel cycle development, uranium was enriched via a different process: gaseous diffusion. This older technique, which predominated from the end of World War II through to the end of the 20th Century, involved pumping UF_6 through diffusion chambers, each containing a permeable membrane. Lighter $^{235}UF_6$ would flow through the membrane at a slightly higher rate than $^{238}UF_6$, again producing an enriched product stream on the opposite side of the membrane from the feed connection, and a tails stream containing a lower ^{235}U concentration. While the principle of cascades and stages was also used in gaseous diffusion plants (GDPs), the separation effect in each diffusion chamber, however, was far smaller than that generated in centrifuges. While GCEPs typically require approximately 10-20 stages to produce a product

[4] Soubbaramayer, "Centrifugation," in *Uranium Enrichment*, ed. Stelio Villani, Topics in Applied Physics, Vol. 35 (New York: Springer-Verlag, 1979), 186; Karl Cohen, *The Theory of Isotope Separation as Applied to the Large-scale Production of U-235* (New York: McGraw-Hill, 1951), 119–124.

enriched to 3–5%, GDPs required approximately 1000 stages to accomplish the same task. Additionally, GDPs consumed far more energy and were costlier to operate, as UF_6 had to be pumped between diffusion chambers, while in a GCEP cascade, UF_6 flow from stage to stage is induced by the rotation of the centrifuges themselves, and no additional energy input required. As centrifuge technology proved itself to be increasingly economical and reliable over the late 20th Century, capacity previously fulfilled by gaseous diffusion plants was replaced by centrifuge enrichment.

GDP safeguards are not discussed in depth in this work. There are many reasons for why GCEP safeguards have greater relevance to contemporary international security, even beyond the absence of GDPs in the current enrichment market and the unlikelihood of the construction of any new GDPs in the foreseeable future. Even when gaseous diffusion dominated the enrichment market, GDP safeguards were a less pressing issue, as these facilities were generally housed in Nuclear Weapon States (NWS), and with the exception of the French Eurodif facility, were not subject to international safeguards. By contrast, States without nuclear weapons spearheaded early centrifuge development efforts. These States began deploying GCEP technology at a pilot scale shortly after the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) entered into force, which they had signed and were expected to ratify as Non-Nuclear Weapon States (NNWS). As NNWS are obliged under Article III(1) of the NPT to accept IAEA safeguards on all nuclear material, the application of NPT safeguards at GCEPs has been pertinent ever since the entry into force of the treaty itself.

The stakes for safeguards verification at GCEPs, versus GDPs, were also higher. While both facility types, when used for civil purposes, would generally produce uranium enriched to no more than approximately 5%, modifying a GDP to produce weapons-usable material would require months of equilibration time before HEU could be produced, during which highly visible changes in plant configurations could be detected with ease. Reconfiguring a GDP would also likely be difficult and costly. GCEPs, by contrast, could be modified more easily and equilibrate far more quickly, offering a far more accessible path to weapons material.[5]

The potential for GCEPs to be modified to produce HEU easily and quickly forms the basis of a challenge that is unique to GCEP safeguards: inspectorates must face the task of verifying in a timely manner that enrichment facilities are not misused to produce material enriched to higher-than-declared levels, particularly weapons-usable HEU, using undeclared or declared feed material. Inspectorates must carry out this mission in addition to verifying material accountancy at GCEPs—in other words, verifying that material is not diverted from peaceful to non-peaceful uses, as is done for all material under safeguards, and at every location where international safeguards are applied. Because of the additional and unique possibility of misuse resulting in the production of weapons-usable quantities of fissile material, the continued effectiveness of international safeguards at GCEPs is particularly crucial.

Current political and technical conditions put GCEP safeguards under particularly high scrutiny. A large portion of the verification activities under the Joint Comprehensive Plan of Action (JCPOA) focus on Iran's centrifuge enrichment activities. Some of these measures go beyond

[5] A.S. Krass, P. Boskma, B. Elzen, and W.A. Smit, *Uranium Enrichment and Nuclear Weapon Proliferation* (London: Taylor & Francis, 1983), 127–128.

those authorized under Iran's comprehensive safeguards agreement (CSA) and provisional Additional Protocol (AP) with the IAEA, made pursuant to its status as a NNWS. These measures generate additional confidence that Iran's nuclear fuel cycle activities are peaceful in nature. However, they are time limited. At some point in the future, after they expire (or if the JCPOA is terminated), IAEA safeguards activities in Iran must continue to be effective in deterring misuse of nuclear material and technology by risk of early detection, and must also be perceived to be so by the international community.[6] In particular, the JCPOA's restrictions on enrichment capacity and LEU feedstock quantities were designed to limit the amount of time necessary to produce enough material for a nuclear weapon (i.e. its 'breakout time') to 12 months.[7] In the absence of these limits, when Iranian gas centrifuge enrichment capacity grows, thus reducing Iran's breakout time, questions will likely emerge over whether current safeguards capabilities provide a sufficiently rapid detection capability to deter misuse of a facility. Questions concerning safeguards effectiveness, however, need not only be limited to IAEA verification in Iran. In recent years, safeguarded commercial GCEPs worldwide have also grown larger in capacity, raising the question of whether inspectorates are suitably equipped to detect HEU production at a facility in a timely manner, were it to occur.

Additionally, at a global level, international safeguards must not only be regarded as credible, but also as equitable among stakeholders. Safeguards inspectorates require financial contributions,

[6] The objective and intended effect of safeguards, as stated by the IAEA, "is to deter the spread of nuclear weapons by the early detection of the misuse of nuclear material or technology. This provides credible assurances that States are honouring their legal obligations that nuclear material is being used only for peaceful purposes." See International Atomic Energy Agency, "Basics of IAEA Safeguards," accessed March 2, 2018. https://www.iaea.org/topics/basics-of-iaea-safeguards.

[7] "The Historic Deal that Will Prevent Iran from Acquiring a Nuclear Weapon," Obama White House Web Archive (U.S. National Archives and Records Administration, 2016), accessed March 27, 2018, https://obamawhitehouse.archives.gov/node/328996.

human capital, and technical cooperation from Member States and facility operators in order to carry out their mission. Regardless of their credibility, if safeguards activities are viewed by stakeholders as unfair or excessively burdensome, the capability of inspectorates will suffer, as resources and collaboration are withdrawn or fail to match growing demands on the safeguards system. States and facility operators must perceive the benefits of their participation and engagement in international safeguards regime to exceed the costs and inconvenience involved with its implementation.

Research Questions and Thesis

What can be done to ensure the effectiveness and efficiency of international safeguards at GCEPs, both now and in the near- to mid-term future (targeting the sunset of the JCPOA's enhanced verification provisions, as well as those limiting breakout time), in the face of the growing political attention to GCEP safeguards, as well as the growth in GCEP capacity over recent decades that has led to centrifuge enrichment dominating today's uranium enrichment market? This dissertation aims to address this question.

Assessing what needs to be done for current and future GCEP safeguards requires a detailed understanding of why and how GCEP safeguards exist as they do today. Prior to the completion of this dissertation, however, a publicly available knowledge base of origins and history of GCEP safeguards did not exist. Thus, while the aim of this research project is to be forward looking—with the ultimate goal of providing actionable policy conclusions for facilitating the development of a strong international safeguards system in years to come—this dissertation also studies the path

that led to the present state of GCEP safeguards. A particular focus of this portion of the research project is to investigate how international safeguards inspectorates, technology holder States, and GCEP operators have addressed GCEP safeguards across time. Special attention is given to how parties addressed verifying the absence of facility misuse over the course of this study. As will be discussed in subsequent chapters, stakeholders did not only have to grapple with the high stakes of verifying the absence of facility misuse—in addition, new concepts had to be developed from scratch for addressing this safeguards objective. Before GCEPs entered the landscape, safeguards inspectorates had only dealt with material accountancy verification. In a sense, international safeguards would have to be 'reinvented' to meet this new mission. The title of this dissertation alludes to historical efforts to design safeguards approaches to address GCEP misuse, as well as contemporary considerations on ensuring continued GCEP safeguards effectiveness.

Archival evidence shows that discussion on how to deal with the novel problem of GCEP misuse took place in a highly politicized environment, wherein stakeholders debated issues ranging from the applicability of IAEA CSAs to undeclared or clandestine activities, to the equitability of safeguards application in NNWS vs NWS, to security risks inherent to inspector access to sensitive facility areas, to the perceived effectiveness of GCEP safeguards in the eyes of other States, particularly members of the Warsaw Pact.

This work argues that the political conditions leading up to the agreement of the first model IAEA safeguards approach for GCEPs led stakeholders to ultimately address safeguards measures for addressing misuse primarily through political channels without clearly defining detection probability and timeliness targets, and with technical considerations playing a secondary role.

Furthermore, politically-driven solutions for addressing misuse were necessitated by the political environment at the time. With the exception of the JCPOA, which authorizes safeguards measures additional to those sanctioned by Iran's CSA and provisional Additional Protocol (AP), as well as measures addressing the possible presence of undeclared material and equipment, misuse verification at GCEPs has essentially continued without major evolution since, both due to technical constraints verification technology, as well as the continued presence of political constraints. As future paths for maintaining the effectiveness of GCEP safeguards are considered, it will be vital to consider both the technical realities of how quickly and easily a GCEP might be used to produce fissile material, but also the past, present, and future political context that will shape the toolbox of measures from which inspectorates will be able to draw. In short, agreement—i.e. the reinvention—of effective GCEP misuse verification measures has been difficult at the beginning, has been difficult since then, is difficult now, and will be difficult in years to come if substantial gains in effectiveness are desirable. The results of this research indicate that such improvements are warranted and suggest ways to reduce difficulties in implementing them.

Knowledge Gaps

Historical accounts on the negotiation of GCEP safeguards measures are sparse. It is common knowledge in the safeguards community that an ad hoc technical effort known as the Hexapartite Safeguards Project (HSP), which ran from 1980–1983, established the widely accepted framework for IAEA safeguards activities at GCEPs. HSP participants included Australia, the Federal Republic of Germany (FRG), the Netherlands, Japan, the United Kingdom and United States, the IAEA and Euratom. It is also well known that the HSP resolved the particularly difficult question

of whether IAEA inspectors would be given access to the parts of GCEPs where centrifuges were housed, known as cascade halls or cascade areas. While the inspectorates and some States supported cascade access, other States were strongly opposed to this idea, primarily over concerns about the possibility of inspectors gaining commercially or security sensitive information while carrying out safeguards activities. The HSP ended with a consensus that all six GCEP technology holder participants would allow the IAEA to conduct short-notice unannounced inspections of cascade areas known as Limited Frequency Unannounced Access (LFUA) inspections, along with a generic framework for GCEP safeguards activities that could be used as a starting point for safeguards activities at individual plants. Literature on the HSP, however, is limited to two retrospective papers by former HSP delegates,[8] along with two reports on the safeguards measures agreed by the project: one in English, and one in German.[9] A detailed account of what took place during the HSP does not exist in the published literature. At the beginning of this dissertation research project, questions remained over how individual States, as well as the three European States (known as the 'Troika') that were jointly pursuing GCEP development and commercialization, developed their negotiating positions. The precise terms and conditions, under which the HSP safeguards approach was negotiated, were unknown. No secondary literature describes what took place during the HSP. This dissertation fills this knowledge gap.

[8] J. Christian Kessler, "Technical Negotiations in a Political Environment," *The Nonproliferation Review* 20, no. 3 (2013): 493–508; K. Naito, "Hexapartite safeguards project: A retrospective," IAEA-CN-148/97, in *Proceedings of an International Safeguards Symposium on Addressing Verification Challenges: Contributed Papers* (Vienna: International Atomic Energy Agency, 2007), 609–616.

[9] Joerg H. Menzel, ed. "Safeguards Approach for Gas Centrifuge Type Enrichment Plants," *Journal of Nuclear Materials Management* 12, no. 4 (1983): 30–37; R. Buttler et al., "Internationale Safeguards für Zentrifugenanlagen: Konzepte und Verfahren zur Kernmaterialüberwachung und das internationale Hexapartite-Projekt," Jül-Spez-216 (Jülich: Kernforschungsanlage Jülich, August 1983).
The verification measures, as agreed at the final HSP plenary meeting, are reproduced in Chapter 2.2 of the Jülich report.

There existed further mysteries, however, beyond what happened during the HSP. The most striking question at the outset of this research concerned what took place in the years preceding the HSP. In the summer of 1973,[10] three years after NPT's entry into force, two pilot GCEPs went into operation in Almelo, Netherlands, which had signed the NPT as a NNWS, and was due to ratify the treaty following negotiation of a safeguards agreement between the IAEA and Euratom, of which it was a member. At this point, international safeguards at GCEPs, no less enrichment plants, were uncharted territory: neither inspectorate had ever applied safeguards at an enrichment facility. An entire decade would follow before routine IAEA safeguards were applied at Almelo, which by 1983 had grown into a commercial-scale enrichment facility. Although safeguards at Almelo were delayed initially by NPT ratification by Euratom Member States and entry into force of the IAEA-Euratom agreement, which occurred in 1977, the fact that a GCEP was operated for a decade in an NPT NNWS without routine IAEA safeguards is remarkable. This warrants an explanation in itself. It is equally puzzling why a 'facility attachment' (FA) detailing routine safeguards activities for Almelo had not been agreed in the four years from when enrichment activities began at the site, up to the implementation of the IAEA-Euratom safeguards agreement. Until this dissertation project began, no publicly available research had been conducted on this 'lost decade' of enrichment safeguards.

While the published literature, until now, has lacked a historical context and narrative for the genesis of GCEP safeguards, substantial information on the history of GCEP safeguards is available. Much of this information was formerly controlled by national governments, and now has been reviewed and released through official channels. This dissertation draws upon a variety

[10] R.B. Kehoe, *The Enriching Troika: A History of Urenco to the Year 2000* (Marlow, UK: Urenco Limited, 2002), 61.

of sources including the U.S. National Archives and Records Administration's (NARA's) online database, as well as the NARA Archives II facility in College Park, MD, The National Archives of the United Kingdom, the German Federal Archive (Bundesarchiv), and the Political Archive of the German Foreign Office (Auswärtiges Amt). Prior to this dissertation, no archival research had been undertaken on the history of GCEP safeguards. Archival sources and non-archival sources are listed separately in the bibliography for each chapter. In each chapter bibliography, archival sources are cited at the series level. Complete information for archival sources is given in footnotes throughout the text. Some citation footnotes for documents obtained from the U.S. NARA contain an "AAD" designator, indicating that the document was sourced from NARA's online Access to Archival Databases (AAD) portal at https://aad.archives.gov, specifically from the "Central Foreign Policy Files 1973–1979" series in Record Group 59. The remainder of the U.S. NARA documents were obtained at its Archives II facility located in College Park, MD, and are listed at the Record Group, series, box, and folder level. Citations for UK-sourced documents include the "TNA" designator, along with a department code (e.g. FCO), a series number and piece number, and as available, item numbers, with a forward slash separating each information level. Documents obtained in Germany are either designated "BArch" (an abbreviation for "Bundesarchiv") or "PA AA" (an acronym for "Politisches Archiv des auswärtigen Amtes") followed by a department code (e.g. B 196) and a folder number. In addition, a Freedom of Information Act (FOIA) request to the U.S. Department of Energy Office of Science and Technical Information (OSTI), #OSTI-2017-00114-F, was made in performing this research.

Dissertation Structure

This dissertation charts the past, present, and future of GCEP safeguards—in particular, political and technical dynamics connected to the issue of misuse verification—over the following eight chapters.

Chapter 2 provides context for this research by providing an overview of the legal frameworks for IAEA and Euratom safeguards, as well as an introduction to the types of safeguards activities that are implemented at GCEPs.

Chapters 3–7 detail the history of GCEP safeguards, with Chapters 3–6 drawing primarily from archival sources. The first of the historical chapters, Chapter 3, discusses relevant developments to GCEP safeguards from World War II up to the start of multilateral dialogue on the issue in the early 1970s. During this period, uranium enrichment (beyond laboratory-scale experiments) lay strictly in the hands of NWS, and a stringent quadripartite classification system for centrifuge enrichment technology was set up in the United States and in the Troika countries. Meanwhile, Cold War dynamics between the United States and Soviet Union stoked fears that the effectiveness of GCEP safeguards, particularly at Almelo, would become a political issue within the United Nations system, instead of being confined to the IAEA and Euratom. Under this specter, technology holders quietly sought to mold verification concepts developed by inspectorates, in line with their own ideas. Chapter 4 covers the first period of formal international dialogue on GCEP safeguards in the early to mid-1970s, which began with a working group organized by the IAEA in June 1972. In this interval, while deep disagreement existed between U.S. and European

stakeholders over the safeguards technology and inspection effort to be applied at GCEPs, Americans and Europeans colluded to ensure that a 'working hypothesis' would be accepted by the IAEA that assumed the exclusion of inspectors from cascade areas. In the meantime, a conflicting precedent was set by Euratom, which successfully fought Troika efforts to prevent Euratom inspectors from visiting cascade halls at Almelo. Chapter 5 examines the GCEP safeguards debate from the mid-1970s up to the beginning of the HSP. This period ended with a standoff over whether IAEA inspectors were to be granted cascade access at Almelo. While internal disagreement within the Troika had developed over this issue, the Troika as a matter of group policy was still opposed to the cascade access. During the design verification process for Almelo in the late 1970s, however, the IAEA moved to abandon the 'working hypothesis,' and instead began to argue that cascade access was indeed necessary for effective safeguards. The resulting deadlock motivated the United States to propose establishment of the HSP, conceived as a technical effort solely dedicated to development of an IAEA safeguards approach for GCEPs. Chapter 6 concerns the HSP itself, with a particular emphasis on how participants first created the conditions that allowed constructive work to proceed, as well as on the negotiation of the political compromise that ultimately allowed agreement over LFUA to coalesce. Chapter 7 discusses developments in GCEP safeguards to the present day, arguing that while substantial effort has been devoted to improving misuse verification capabilities, little has been implemented—in practice—to address the critical objective of detecting higher-than-declared enrichment levels and HEU production in a timely manner.

Chapter 8 presents a technical analysis of modern-day safeguards needs at commercial GCEPs, making use of a Python model developed by the author to investigate how HEU production could

take place at a generic reference GCEP similar in capacity to large-scale facilities currently under international safeguards. Results from this model are used to produce fissile material production estimates. The results of these calculations are used to motivate an argument for the further development of unattended monitoring systems equipped with remote data transmission capabilities that could potentially provide a real-time detection capability for HEU production. A potential toolbox of these systems is presented at the end of the chapter.

Chapter 9 synthesizes the information presented in this dissertation, drawing observations and lessons learned from previous chapters to offer recommendations on future steps for GCEP safeguards. In particular, this final chapter addresses the question of how to implement strengthened GCEP verification in an environment where international safeguards are under ever-growing political scrutiny, and where individual States and facility operators may be reluctant to subject themselves to additional safeguards measures.

Of course, this dissertation considers several other policy-relevant questions, which organically arise from the historical narrative of enrichment safeguards development. This story, for example, is incomplete without a discussion of the role of knowledge asymmetry between technology holders and inspectorates regarding technical capabilities of facilities, during safeguards negotiations. Additionally, given the key role of the Dutch-West-German-British Troika in GCEP safeguards, the political dynamics between these three States on this issue are an essential part of the story. The question of "how much verification is enough?" as the evidence shows, was equally salient in the early 1970s as it is today for enrichment verification. Over the following eight chapters, this question too is given attention, taking into account evolving GCEP capabilities. In

addition, a reader of this work could consider it as a case study in the politics of nuclear nonproliferation, focusing on understanding the conditions that cause safeguards talks to fail and succeed, and on conditions that promote political bargaining over technical analysis, or vice versa. Conversely, this work can also be read a history of the development of GCEP safeguards concepts and technology. But while this dissertation deliberately seeks to establish a definitive narrative for both the politics and technology of GCEP safeguards, it would behoove any reader not to consider one facet without the other. The history and present condition of GCEP safeguards is both a story of technology driving policy, and of policy driving technology. Understanding this symbiotic relationship will be crucial to charting an optimal path forward for GCEP safeguards, subject to both technical and political constraints, which this research ultimately aims to do.

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Chapter 2 – The Fundamentals of Gas Centrifuge Enrichment Plant Safeguards: Material Accountancy and Misuse Verification

Chapters 3-7 of this dissertation analyze the development of international safeguards approaches, particularly those addressing facility misuse, for gas centrifuge enrichment plants (GCEPs), from the end of World War II to the present day. Before delving deeply into these arcana, however, it is valuable to first establish 'goalposts' for GCEP safeguards. What are the objectives of international safeguards inspectorates at GCEPs? By what technical means and under what authority do inspectorates meet safeguards objectives? How does one evaluate safeguards effectiveness?

The purpose of safeguards on nuclear material, at the most fundamental level, is to verify that nuclear material destined for a *declared* purpose is not requisitioned, or *diverted*, to another purpose. Safeguards on nuclear material can be applied in a wide array of operational and legal contexts. In a Nuclear Weapon State (NWS), for example, safeguards may be applied on material destined for weapons purposes (along with other measures, e.g. physical security), to ensure that it is not misappropriated by malicious actors from within or outside the nuclear weapons complex. More typically, however, the concept of safeguards connotes verifying that nuclear material used in peaceful purposes, i.e. in the civil nuclear fuel cycle, or in peaceful applications of nuclear technology, is not diverted from these purposes. Civil nuclear safeguards can be undertaken by domestic authorities within a State, often as part of a State's regulatory or licensing system for nuclear fuel cycle activities. Safeguards are also carried out at an international level, which is the focus of this dissertation. As mentioned in the previous chapter, three authorities, known as inspectorates, implement international safeguards: the International Atomic Energy Agency

(IAEA), the European Atomic Energy Community (Euratom), and the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC).

As mentioned in the introduction, these inspectorates also face the safeguards objective of verifying the absence of GCEP misuse, in addition to providing assurance of the non-diversion of declared nuclear material via material accountancy verification. While the most serious form of misuse involves use of a GCEP to produce HEU using declared or undeclared material, misuse also encompasses production of material enriched beyond declared levels, as well as the introduction of undeclared feed to produce undeclared material at or below declared enrichment levels. This chapter discusses the objectives and means by which inspectorates address diversion and misuse at GCEPs. First, however, an introduction to the legal context for international safeguards is provided.

The Legal Context for International Safeguards

International safeguards are and have been implemented under a complex web of legal arrangements. From the IAEA's establishment under its 1957 Statute,[1] to the implementation of NPT safeguards in 1972, IAEA safeguards were essentially carried out on a piecemeal basis known as 'item-specific safeguards,' either upon a unilateral decision of a State to place material under safeguards,[2] or pursuant to technology transfer agreements facilitated by the IAEA, or transfer

[1] International Atomic Energy Agency, "The Statute of the IAEA" (1956), accessed March 8, 2018, https://www.iaea.org/about/statute.

[2] For example, the United States opted to place four reactors under IAEA safeguards in 1961. See Allan McKnight, *Atomic Safeguards: A Study in International Verification* (New York: United Nations Institute for Training and Research, 1971), 64.

agreements between nations requiring safeguards on transferred material or facilities. At this time, IAEA safeguards agreements were drawn up on a facility-specific basis. The advent of the NPT, however, dramatically transformed the IAEA's safeguards role. Under the NPT, States that had not tested a nuclear explosive device prior to January 1, 1967 could only join the Treaty as Non-Nuclear Weapon States (NNWS), obliging themselves to forswear the development or acquisition of nuclear weapons.[3] As part of this commitment, NNWS are also required to accept safeguards on "all source or special fissionable material in all peaceful nuclear activities within the territory of such [a] State, under its jurisdiction, or carried out under its control anywhere,"[4] under a so-called comprehensive safeguards agreement (CSA). CSAs are closely based on a model CSA, known as "INFCIRC/153 (corrected)" and hereafter designated INFCIRC/153,[5] which was negotiated in the early 1970s by a dedicated committee within the IAEA Board of Governors, known as Committee 22. This document details the respective obligations of the IAEA and State authorities in implementing comprehensive safeguards, including *inter alia* the requirement for the contracting State to establish a "system of accounting for and control of all nuclear material" (SSAC), guidelines for the provision of information and material declarations to the IAEA, guidelines for verification activities (including inspections), and conclusion of more detailed subsidiary arrangements to the CSA.

[3] "Treaty on the Non-Proliferation of Nuclear Weapons (NPT)," INFCIRC/140 (Vienna: International Atomic Energy Agency, April 22, 1970), https://www.iaea.org/sites/default/files/publications/documents/infcircs/1970/infcirc140.pdf.
[4] "Treaty on the Non-Proliferation of Nuclear Weapons (NPT)," Art. III.1.
[5] "The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons," INFCIRC/153 (corrected) (Vienna: International Atomic Energy Agency, June 1972).

Fundamentally, IAEA safeguards rely on the implementation of material accountancy, whereby State authorities provide material balance data to the IAEA (via the SSAC), and the IAEA verifies these declarations through independent measurements and observation.[6] Under this system, the nuclear material inventory within a facility is divided up into material balance areas (MBAs), in such a way that allows for independent verification of flows into and out of each MBA, as well as the inventory of each MBA itself.[7] MBA inventories and flows between MBAs are verified at key measurement points (KMPs). Each KMP is designated as an inventory KMP or a flow KMP, depending on whether it is used for inventory or flow measurements. Material accountancy is complemented by the IAEA's use of containment and surveillance (C/S). Containment can refer to physical characteristics of MBAs (e.g. reinforced concrete walls) that ensure the completeness of the IAEA's flow and inventory measurements, by preventing clandestine flows of nuclear material between MBAs. In addition, containment can also be informally used to describe the packaging of nuclear material within an MBA (e.g. a steel UF_6 cylinder wall). Surveillance is used to verify the integrity of containment, particularly where it is not naturally intact, for example, at a door between MBAs. This most commonly involves the use of cameras and/or tamper-resistant seals. C/S at a door might involve the placement of a camera facing the portal, or the placement of a tamper-indicating seal on the door if it is not used by the operator. The purposes of C/S are to ensure that nuclear material only passes between MBAs at KMPs where flows can be independently verified by the IAEA, and to expedite inventory verification by establishing continuity of knowledge (CoK) on items that have been previously verified (a tamper-indicating seal placed on a UF_6 cylinder, immediately after it has been weighed, can be used to show at a later date that it still contains the same amount of material that the time of its weighing). MBA

[6] Ibid., para. 7.
[7] Ibid., para. 110.

boundaries, containment integrity, surveillance measures and key measurement points are determined by IAEA inspectors in Design Information Verification (DIV),[8] during which inspectors verify that facility design characteristics declared to the IAEA are correct and complete. During DIV, the IAEA selects a collection of KMPs, as well as a set of locations at which C/S measures are to be deployed, which collectively provide the necessary and sufficient information to verify the MBA inventories and flows of nuclear material between MBAs for the entire facility. These points, taken together, are known as *strategic points*.[9]

Subsidiary arrangements provide specific procedures and lines of communication necessary for the application of safeguards measures given in INFCIRC/153. These documents consist of a General Part, which applies to all nuclear activities in the State,[10] as well as separate documents known as Facility Attachments (FAs) that detail the nature of safeguards activities to be undertaken at each particular facility, as well as the designation of MBAs, key measurement points, and strategic points. FAs are negotiated after DIV has taken place for a facility. Once an FA has been concluded, *routine inspections* can subsequently take place, during which IAEA inspectors may only perform activities at strategic points within the facility.[11] As of December 31, 2016, 181 States had safeguards agreements in force with the IAEA, of which 173 were CSAs,[12] making INFCIRC/153-type safeguards the IAEA's predominant safeguards undertaking at present.

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[8] Ibid., para. 48.
[9] Ibid., para. 76c.
[10] International Atomic Energy Agency, *IAEA Safeguards Glossary, 2001 Edition*, International Nuclear Verification Series No. 3 (Vienna: International Atomic Energy Agency, 2002), 10.
[11] Prior to the completion of a facility's FA, ad-hoc inspections can take place, during which inspectors may access any location where declared information or any prior inspection indicates that nuclear material is present. See "The Structure and Content of Agreements…," INFCIRC/153 (corr.), para. 76a.
[12] The remaining 8 States consist of the five NPT Nuclear Weapon States (China, France, Russia, the United Kingdom and the United States), and 3 NPT non-parties. The NPT NWS each have Voluntary Offer Agreements (VOAs) that subject portions of or all (depending on the State) civil nuclear fuel cycle facilities

Since the NPT's entry into force, the IAEA's safeguards system has evolved incrementally. Immediately following the entry into force of the NPT, the IAEA concentrated its comprehensive safeguards efforts on verifying the correctness of State declarations—that declared material within facilities declared by each State was accounted for. Verifying the completeness of declared information, i.e. verifying the absence of undeclared nuclear material and activities, was a far lower priority.[13] This mode of implementation reflected the IAEA's safeguards *modus operandi* from prior to the NPT—providing credible assurance of the non-diversion of declared nuclear material within safeguarded facilities, but now applied to all facilities within a given State. At the time of the negotiation of the NPT and INFCIRC/153, assumptions were made by some actors that NNWS parties would never act in bad faith (having demonstrated their commitment to nonproliferation by accepting comprehensive safeguards),[14] or that undeclared activities would be unearthed via other means, such as national intelligence capabilities.[15] But although an INFCIRC/153-type

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to IAEA safeguards. India, Israel, and Pakistan are not NPT parties, but still have item-specific safeguards agreements in place with the IAEA. Note that 12 NPT parties have yet to conclude a CSA with the IAEA, as required by the NPT. See International Atomic Energy Agency, "Safeguards Statement for 2016" (Vienna, June 14, 2017), https://www.iaea.org/sites/default/files/statement_sir_2016.pdf.

[13] Michael Rosenthal et al., *Review of the Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency for the Application of Safeguards*, Vol. I/III, BNL-90962-2010 (Brookhaven National Laboratory, January 2010), 2.

[14] Most notably, the FRG government would broadcast this rhetoric in talks on GCEP safeguards in the 1970s and 1980s, as will be discussed.

[15] The following exchange took place in a 1968 U.S. Senate Committee on Foreign Relations hearing on the NPT, prior to its ratification:

> Senator Claiborne Pell (D-RI): Will the International Atomic Energy Agency inspection be restricted only to the declared peaceful nuclear facilities or will they also apply to the undeclared or clandestine facilities? How will they be sought out?
>
> Secretary of State Dean Rusk: The undeclared and clandestine?
>
> U.S. Arms Control and Disarmament Agency Director William C. Foster: The IAEA inspection would only be as to declared. If there were undeclared, if they were found, this would be a breach of the treaty.

agreement gave the IAEA and a State a respective mandate and obligation to apply safeguards on all nuclear material (repeating language from paragraph III.1 in the NPT), in time, it became clear that the specific tools in INFCIRC/153 were not sufficiently strong to provide assurances of the absence of undeclared material and activities.

The prevailing thought regarding IAEA safeguards and undeclared activities would change during the early 1990s, amidst the aftermath of the discovery of a clandestine nuclear weapons program in Iraq after the first Gulf War, as well as the implementation of NPT safeguards in South Africa, which had previously developed nuclear weapons before joining the NPT, as well as in North Korea, which sought to deceive the IAEA during initial verification activities under its CSA. All three of these scenarios underscored that an independent IAEA ability to detect undeclared material and activities was vital to the credibility of its safeguards system, and that the contemporary approach to IAEA safeguards implementation needed to be strengthened. In 1993, the IAEA embarked on a two-year project dubbed 'Programme 93+2,' which investigated possible measures that could improve its ability to verify the completeness of States' declared nuclear

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> Pell: But under the treaty there is no provision for searching out the clandestine?
>
> Foster: No, sir.
>
> Pell: Just as there is no sanction?
>
> Foster: But there would be great alertness on the part of many, including ourselves, on that latter point, Senator.

This dialogue is reproduced in Pierre-Emmanuel Dupont, "Interpretation of Nuclear Safeguards Commitments: The Role of Subsequent Agreements and Practice," in *Nuclear Non-Proliferation in International law – Volume II*, ed. J.L. Black-Branch and D. Fleck (The Hague: T.M.C. Asser Press, 2016), 41. Original record: U.S. Government Printing Office, "Hearings before the Committee on Foreign Relations: Treaty on the Nonproliferation of Nuclear Weapons," 90th Congress, 2nd Session (Washington, July 1968), 52.

activities. Programme 93+2 identified the use of some tools, including the use of open source information and environmental sampling at declared facilities, which could be deployed under the IAEA's existing authority. These measures were designated as 'Part I' measures. Other measures, named 'Part II' measures, including expanded State declarations covering information on imports and exports of sensitive equipment, nuclear fuel cycle research activities and mining activities, for example, required additional authority on the part of the IAEA. The latter measures were implemented in a Model Additional Protocol (AP), approved by the IAEA Board of Governors in 1997 and published as INFCIRC/540.

States are not required to adopt an AP to their existing safeguards agreements, but there exist incentives to do so, beyond demonstrating commitment to the nonproliferation regime or its norms. From a practical perspective, implementation of an AP gives the IAEA the ability to determine the absence of undeclared nuclear material or activities within a State. An IAEA conclusion of both the non-diversion of declared nuclear material from peaceful activities, as well as of the absence of undeclared nuclear material or activities within a State, constitutes the so-called 'broader conclusion' (BC). Once a State has received a BC, the IAEA can then reallocate its application of safeguards activities within a State, now under the assumption that no clandestine material or facilities are at the potential disposal of a State, thus likely reducing its safeguards effort. This streamlining of safeguards measures is known as Integrated Safeguards (IS). As of the end of 2016, 124 States had an AP in force, and IS was implemented in 57 States, plus Taiwan.[16]

[16] International Atomic Energy Agency, "Safeguards Statement for 2016."

During the mid-1990s, amidst efforts to strengthen safeguards, the IAEA began setting up State Evaluation Groups (SEGs)[17] to more systematically and holistically consider State nuclear fuel cycle activities, prior to drawing safeguards conclusions. Application of IS, following implementation of APs, was a step towards optimizing resources and the effectiveness of safeguards by allocating resources on a State-by-State basis. By the early 2010s, the IAEA embarked on further steps to tune its allocation of resources, and branded these efforts under the umbrella term, 'State-Level Concept' (SLC). The SLC calls for the development of customized State-Level Approaches (SLAs) to guide the implementation of safeguards in all States with safeguards agreements with the IAEA. In States with SLAs, safeguards activities are no longer designed around a particular facility alone, and are instead conceived with other nuclear fuel cycle facilities in the State along with other national characteristics, known as State-Specific Factors, in account.[18] As of the end of May 2017, the IAEA had updated SLAs for 53 States (plus Taiwan) under IS, plus 13 additional States.[19]

[17] International Atomic Energy Agency, "Supplementary Document to the Report on The Conceptualization and Development of Safeguards Implementation at the State Level (GOV/2013/38)," GOV/2014/41, (Vienna, 2014), 9. https://armscontrollaw.files.wordpress.com/2014/09/iaea-state-level-safeguards-document-august-2014.pdf.

[18] The six State-Specific Factors are:

i) the type of safeguards agreement in force for the State and the nature of the safeguards conclusion drawn by the Agency;
ii) the nuclear fuel cycle and related technical capabilities of the State;
iii) the technical capabilities of the State or regional system of accounting for and control of nuclear material (SSAC/RSAC);
iv) the ability of the Agency to implement certain safeguards measures in the State;
v) the nature and scope of cooperation between the State and the Agency in the implementation of safeguards; and
vi) the Agency's experience in implementing safeguards in the State.

See ibid. 5–6.

[19] Therese Renis et al., "Recent Progress in the Implementation of Safeguards at the State-level," Proceedings of the 58th Annual Meeting of the Institute of Nuclear Materials Management (Indian Wells, CA, 2017).

The legal underpinnings for Euratom safeguards are slightly different to those of the IAEA, although strong connections between the work of the two inspectorates exist. Euratom, for its first two decades, functioned primarily under its statutory authority through Chapter 7 of the 1957 Treaty of Rome[20] (also known as the Euratom Treaty, to differentiate it from the treaty, also signed in Rome in 1957, that established the European Economic Community). Article 77 of the original, unamended Treaty established the purpose of Euratom safeguards within its Member States,[21] which is to verify that "ores, source materials and special fissile materials are not diverted from their intended uses as declared by the users," and "the provisions relating to supply and any particular safeguarding obligations assumed by the Community under an agreement concluded with a third State or an international organisation are complied with."[22]

During negotiation of the NPT, the question arose as to whether Euratom safeguards or IAEA safeguards should fulfill the NPT's Article III verification mandate. This question was addressed in the early 1970s, through negotiation of the IAEA-Euratom safeguards agreement,[23] INFCIRC/193, which serves as the comprehensive safeguards agreement for all NNWS Euratom Member States. INFCIRC/193 was negotiated so as to preserve Euratom's ability to carry out its statutory mandate, but also to give the IAEA the ability and obligation to independently ensure the application of safeguards on all nuclear material in peaceful activities in States under the

[20] "Treaty establishing the European Atomic Energy Community (Euratom)" (Rome, March 25, 1957), http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:11957A/TXT&from=EN.
[21] The six original members of Euratom were Belgium, France, the Federal Republic of Germany, Italy, Luxembourg, and the Netherlands.
[22] "Treaty establishing the European Atomic Energy Community (Euratom)," art. 77.
[23] "The Text of the Agreement Between Belgium, Denmark, The Federal Republic of Germany, Ireland, Italy, Luxembourg, The Netherlands, The European Atomic Energy Community and the Agency in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons," INFCIRC/193, (Vienna: International Atomic Energy Agency, September 14, 1973).

agreement, without unnecessarily duplicating Euratom's safeguards activities.[24] IAEA inspections in Euratom NNWS would be carried out jointly with Euratom. Under this system, Euratom both assumed the role as the SSAC, in the IAEA's perspective, for each of its Member States, thus constituting a *regional* system of accounting for and control of nuclear material (RSAC). Euratom would act as the interface between the IAEA and the Euratom NNWS subject to the agreement, taking on responsibility tasks including provision of information to the IAEA and negotiation of facility Attachments. Meanwhile, Euratom would also carry out its own verification activities, acting as a safeguards inspectorate in its own right, including the application of powers unavailable to the IAEA, such as the ability to directly sanction both its Member States and facility operators for failure to meet safeguards obligations.[25] After INFCIRC/193 was agreed, Euratom enacted Regulation No. 3227/76[26] to harmonize its terminology and practices with those of the IAEA under the new agreement. In some respects, Regulation 3227/76 served as Euratom's analog to INFCIRC/193 for the IAEA, for example specifying requirements for provision of information by facility operators to Euratom. Procedures for the drafting of Euratom's equivalent of the facility Attachment, known as "particular safeguard provisions" are also contained in Articles 7–8 of Regulation 3227/76.[27]

In the early 1990s, the IAEA and Euratom established the New Partnership Approach (NPA), with the goal of reducing the costs and streamlining safeguards implementation in Euratom NNWS.

[24] Ibid., preamble, arts. 1, 2 and 4.
[25] Wolfgang Kilb, "The Nuclear Safeguards Regime of EURATOM: A Regional Cornerstone of the Verification of Non-Proliferation Obligations in the European Union," in *Nuclear Non-Proliferation in International law – Volume II*, ed. J.L. Black-Branch and D. Fleck (The Hague: T.M.C. Asser Press, 2016), 161–164.
[26] "Euratom Regulation 3227/76," *Official Journal of the European Union* L 363 (1976): 1–57.
[27] Ibid., arts. 7–8.

The NPA, which is still implemented today, introduced the "one-job-one-person"[28] principle, which essentially allowed for the performance of some inspection activities by only one inspectorate, subject to quality control measures, thereby substantially reducing time spent by inspectors in the field. Furthermore, the NPA allows for the IAEA and Euratom to pool their analysis capabilities, eliminating the need for both organizations to analyze material samples from the same item. The NPA also called for collaboration in R&D work and inspector training, and increased use of technology to replace the need for the physical presence of inspectors.[29]

Euratom Regulation 3227/76 was updated and replaced in February 2005 by Regulation No. 302/2005,[30] which was primarily established to implement the Additional Protocol[31] (INFCIRC/193/Add.8) to the IAEA-Euratom safeguards agreement, which had gone into force the previous year, and which functions as the AP for all Euratom NNWS. Particular safeguards provisions for facilities are negotiated under Article 6 of Regulation 302/2005.[32]

ABACC was created in 1991 as a regional safeguards authority in Argentina and Brazil. The authority of ABACC derives from a bilateral Argentine-Brazilian agreement establishing its two organs (a Secretariat and a supervisory Commission), as well as a Common System of Accounting

[28] International Atomic Energy Agency, "Strengthening the Effectiveness and Improving the Efficiency of the Safeguards System," GC(37/1073) (Vienna, September 6, 1993), 8.
[29] Ibid., 7–8.
[30] "Euratom Regulation 302/2005," *Official Journal of the European Union* L 54 (February 28, 2005): 1–71.
[31] "Protocol Additional to the Agreement between the Republic of Austria, the Kingdom of Belgium, the Kingdom of Denmark, the Republic of Finland, the Federal Republic of Germany, the Hellenic Republic, Ireland, the Italian Republic, the Grand Duchy of Luxembourg, the Kingdom of the Netherlands, the Portuguese Republic, the Kingdom of Spain, the Kingdom of Sweden, the European Atomic Energy Community and the International Atomic Energy Agency in implementation of Article III, (1) and (4) of the Treaty on the Non-Proliferation of Nuclear Weapons," INFCIRC/193/Add.8 (Vienna: International Atomic Energy Agency, January 12, 2005).
[32] "Euratom Regulation 302/2005," art. 6.

and Control of Nuclear Materials.[33] ABACC inspectors are either Brazilian or Argentine nationals. A unique feature of ABACC is that exclusively Brazilian nationals carry out verification activities in Argentine facilities, and vice versa. As both Brazil and Argentina are NPT NNWS, nuclear material in both States are also subject to IAEA safeguards. IAEA verification activities in both nations are governed by a Quadripartite Agreement made between Argentina, Brazil, ABACC, and the IAEA. In a similar way to IAEA-Euratom agreement, the Quadripartite Agreement aims to coordinate efforts between ABACC and the IAEA to avoid unnecessary duplication of inspection effort between the two organizations.[34] As ABACC only came into existence in the early 1990s, it did not participate in the discussions that first established a model safeguards approach for GCEPs.

Material Accountancy

Today, the goals of international safeguards extend beyond the nuclear material accountancy mission, with the imperative to detect clandestine nuclear activities looming large. Nevertheless, the implementation of material accountancy remains the core mission of safeguards, and of in-field inspection activities. It can be conceived as the product of two elements: a system of accounting for nuclear material, and a means for verifying the correctness and completeness of these records. Typically, material accountancy is carried out by a facility operator, under regulatory authority of an SSAC/RSAC, and verification is undertaken by an inspectorate.

[33] "Agreement between the Republic of Argentina and the Federative Republic of Brazil for the Exclusively Peaceful Use of Nuclear Energy" (Guadalajara, Mexico, July 18, 1991).
[34] "Agreement Between the Republic of Argentina, the Federative Republic of Brazil, the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials and the International Atomic Energy Agency for the Application of Safeguards" (Vienna, December 13, 1991).

At the most basic level, a material accountancy system involves keeping records of the amount and type (i.e. chemical constitution and isotopic content, as applicable) of nuclear material within each MBA. This mission includes recording shipments and receipts into and out of each MBA, as well as any processing of the material that take place in the MBA—for example, enrichment, or chemical processing. A training document prepared for the European Safeguards Research and Development Association (ESARDA), lists the following criteria for 'satisfactory' and 'good' recordkeeping:

> "**Criteria for Satisfactory Accounts:** The major objectives of a satisfactory set of accounts are,
>
> - the accounts should describe all the material items making up inventories, shipments and receipts. By description here is meant that the items have identities, implicit or explicit, and an associated declared mass.
> - all the discrepancies, normally measurement errors, between accounting values and true values should be small enough.
> - the accounts should be complete i.e. every object containing nuclear material should be included in the accounts.
>
> **Creating Good Accounts:** Ensuring the quality of the accounting information in the facility database, includes a lot of practical operating aspects such as having,
>
> - a measurement system which provides an accurate quantification of stocks and transfers of material.
> - operating records that document material movements, material locations, identities of items and provide links to related measurement data.
> - accountancy control procedures whereby information is regularly cross-checked against other information to detect incoherencies."[35]

[35] M.T. Franklin, "An Introduction to Statistical Aspects of NM Accountancy and Auditing," in *Nuclear Safeguards and Non-Proliferation: Syllabus of the ESARDA Course*, G. Janssens-Maenhout, ed. (Luxembourg: Office for Official Publications of the European Communities, 2009), 109. http://cvt.engin.umich.edu/wp-content/uploads/sites/173/2014/10/ESARDA-Course-Syllabus.pdf.

Two categories of material inventory records exist: physical inventory and book inventory. Physical inventory refers to the sum of the masses of all batches[36] of nuclear material at a given time in a given MBA,[37] as measured by the operator (and later verified by the inspectorate). The book inventory of an MBA, meanwhile, is the "algebraic sum of the most recent physical inventory of that material balance area and of all inventory changes that have occurred since that physical inventory was taken."[38]

Material accountancy data kept by operators are shared with inspectorates, via State authorities, pursuant to safeguards agreements. INFCIRC/153 paragraphs 56-58 stipulate accounting records requirements for IAEA comprehensive safeguards. The IAEA requires accounting records to be kept that contain all inventory changes, all measurement results that are used for determining the physical inventory of each MBA, and all adjustments and corrections made to inventory changes, physical inventories, and book inventories.[39] Additionally, the IAEA requires that operating records be kept to show how physical inventories were measured, as well as how changes in quantities and the composition of nuclear material took place.[40] Paragraphs 62-67 of INFCIRC/153 delineate requirements for the provision of accounting reports under IAEA safeguards, under which States are obligated to provide inventory change reports (ICRs) and material balance reports (MBRs) for each MBA. ICRs must be submitted as soon as possible, or within 30 days after the end of the month after an inventory change takes place in an MBA, and MBRs must be submitted within 30 days after a physical inventory is taken (which takes place at a frequency determined

[36] Per INFCIRC/153, para. 100, a 'batch' refers to an amount of nuclear material treated as a unit, for accounting purposes.
[37] "The Structure and Content of Agreements…," INFCIRC/153 (corr.), para. 113.
[38] Ibid., para. 102.
[39] Ibid., para. 56.
[40] Ibid., para. 58.

through DIV, taking note of timeliness criteria associated with the material in the MBA).[41] The time between two physical inventory takings (PITs) is known as a material balance period (MBP). Inventory changes from one MBA to another, by convention, are always recorded as reported by the shipping MBA,[42] and thus the book inventories of the shipping and receiving MBAs change by the same magnitude during an inventory change. If it is determined that the receiving MBA did not take in the same amount of material reported by the shipping MBA, the difference in these quantities is recorded as a shipper-receiver difference (SRD),[43] which is recorded as an adjustment to the book inventory of the receiving MBA. SRD typically occurs only when material is transferred between facilities, as the measurements upon shipment and receipt are done independently. At commercial GCEPs under safeguards, physical inventory is taken annually, pursuant to timeliness goals, which will be discussed later in this chapter.

All MBRs are accompanied by a physical inventory listing (PIL) that itemizes all batches of material in a given MBA, listing batch data for each batch. Batch data is defined as the total weight of each item in each batch (along with isotopic composition, for uranium and plutonium). Masses of contained plutonium, total uranium, ^{233}U and ^{235}U are reported in grams, while thorium, uranium and depleted uranium are reported in kilograms.[44] The MBR itself contains the physical inventory at the beginning of the previous period, all inventory changes, the *book* inventory at the end of the

[41] Ibid., para. 63.
[42] International Atomic Energy Agency, "Contents, Format and Structure of Reports to the Agency," Code 10 of *Model Subsidiary Arrangements, General Part*, SG-FM-1172 (Vienna: 2017), 8. https://www.iaea.org/sites/default/files/sg-fm-1170-subsidiary-arrangement-code-10-labelled.pdf
[43] "The Structure and Content of Agreements…," INFCIRC/153 (corr.), para. 114.
[44] Ibid., para. 101.

period, all shipper/receiver differences, the ending book inventory adjusted for SRDs, the ending *physical* inventory, and the observed material unaccounted for (MUF).[45]

MUF is a key concept in material accountancy. In INFCIRC/153, it is defined as the difference between the adjusted book inventory and physical inventory taken at the end of a MBP.[46] MUF can also be expressed, using the definition of book inventory, as the beginning physical inventory, plus inventory changes and SRDs, minus the ending physical inventory. Positive MUF indicates that nuclear material in the book inventory is 'missing,' i.e. that the ending physical inventory is less than the ending adjusted book inventory, and negative MUF indicates the presence of 'extra' material in the measured physical inventory. Contributions to MUF from nuclear material that remains in *item* form through an MBP, such as fuel assemblies, are expected to be close to zero, as the material is contained within the item and losses should not take place, although uncertainties in MUF may still arise through inventory measurement techniques. When nuclear material is processed in *bulk*, however (e.g. during uranium enrichment, UF_6 conversion, or reprocessing), losses are expected to occur in the process equipment, and a non-zero MUF is expected. In a GCEP cascade area, for example, uranyl fluoride deposits can form on the inside of process piping, resulting in the sum of masses in product, tails, and waste streams being less than the amount of material fed into the area. Thus, while non-zero MUF in an MBA made up of itemized nuclear material may be indicative of diversion or an accounting error, non-zero MUF associated with bulk material, even in excess of IAEA significant quantity (SQ) values, may not necessarily be attributable to malicious activity.

[45] Ibid., para. 67.
[46] Ibid., para. 111.

The variance (and standard deviation) of observed MUF, as calculated on the basis of operating records, is an important metric for evaluating the significance of a given MUF. Sources of variability in observed MUF come from systematic and random errors associated with the measurement processes associated with PIT. The total variance of MUF can be calculated using the formula for error propagation of a linear function of k variables,

$$y = \sum_{i=1}^{k} a_i x_i \qquad (2.1)$$

where each x_i is the value taken on by the i-th random variable, and a_i is some constant associated with it. Here, the variance of y, $\sigma^2{}_y$, is given as

$$\sigma^2{}_y = \sum_{i=1}^{k} a_i{}^2 x_i{}^2 + 2 \sum_{i=1}^{k-1} \sum_{j>i} a_i a_j \sigma_{ij} \qquad (2.2)^{47}$$

where σ_{ij} is the covariance between the i-th and j-th random variable. If it is assumed that all sources of error are independent from each other, the second term on the right-hand side of equation 2.2 is equal to zero.

The variance of the observed MUF can subsequently be used in a hypothesis test using the normal distribution, where the null hypothesis is that the observed MUF is equal to zero. If the null

[47] International Atomic Energy Agency, *Safeguards Technical Manual, Part F: Statistical Concepts and Techniques,* Volume 3, IAEA-TECDOC-261 (Vienna: 1982), 104.

hypothesis is not rejected at a given level of significance, then the measured MUF can be attributed to the measurement error used in the physical inventory taking. If the null hypothesis is rejected, this implies that a source of MUF exists other than the measurement error associated with PIT, which could imply the diversion of nuclear material, or the existence of holdup that is unaccounted for. The simple example below, heavily adapted from the IAEA Safeguards Technical Manual (Part F, Volume 3, Example 3.1b), illustrates how MUF can be quantified and analyzed:

Example: Determining the significance of MUF

An MBA consists of a UF_6 cylinder storage area. The MBA is entirely empty at the beginning of the MBP. During the MBP, 10 UF_6 cylinders, containing natural uranium with a total mass of 15390 kgU are transferred into the MBA. No shipper-receiver differences are found. The ending physical inventory of the MBA is taken by weighing each cylinder individually, and summing the masses, yielding 15365 kgU. The ending book inventory is 15390 kgU, and the ending physical inventory is 15365 kgU, giving a MUF of 25 kgU.

During the most recent PIT, cylinders were weighed on 2 days: the first 6 on day 1, and the remaining 4 on day 2.

The model for a single cylinder weighing is given as a function of three random variables δ, θ_1 and ε_{ij} with means equal to zero and nonzero variances:

$$x_{ij} = \mu_{ij} + \delta + \theta_i + \varepsilon_{ij} \qquad (2.3)^{48}$$

where x_{ij} is the observed weight of container j weighed on day i, μ_{ij} the container's true weight, δ is systematic error reflected in all measurements (e.g. due to a scale bias), θ_i is a systematic error that affects all cylinders weighed on day i, and ε_{ij} is a random error.

Standard deviations for δ, θ_1, θ_2 and ε_{ij} are given as: $\sigma_\delta = 0.7\ kg$; $\sigma_{\theta_1} = 1\ kg$; $\sigma_{\theta_2} = 0.8\ kg$; and $\sigma_\varepsilon = 1.5\ kg$, and all covariances are zero.

The equation for MUF is equal to the book inventory minus the ending physical inventory:

$$\begin{aligned} MUF &= 15390 - \sum x_{ij} \\ &= 15390 \\ &\quad - \left(\sum \mu_{ij} + 10\delta + 6\theta_1 + 4\theta_2 + \sum \varepsilon_{ij}\right) \end{aligned} \qquad (2.4)$$

Using equation 2.2, the variance of MUF, $\sigma^2{}_{MUF}$, is given by:

$$\sigma^2{}_{MUF} = 100\sigma^2{}_\delta + 36\sigma^2{}_{\theta_1} + 16\sigma^2{}_{\theta_2} + 10\sigma^2{}_\varepsilon = 117.74\ kg^2 \qquad (2.5)$$

Thus, $\sigma_{MUF} = 10.85\ kg$.

[48] Adapted from Ibid., 105.

In this case, the observed MUF is significant to 2.30 sigma, implying the null hypothesis can be rejected with greater than 95% confidence (>1.96 sigma, or with a false alarm rate of <5%). Therefore, the observed MUF can be attributed to a source other than systematic and random measurement error from the physical inventory taking process.

When calculating the variance of ^{235}U MUF, as is carried out in enrichment facilities, it is necessary to consider both the variance of the U MUF as well as variance in the measured ^{235}U concentration attributable to the measurement techniques used to measure material enrichment. These variances sum to yield the variance of ^{235}U MUF.

At this point, it is important to stress that MUF is determined entirely by the facility operator, and that analysis of MUF alone is clearly insufficient for the verification of material accountancy. In general, there exist three methods for concealing the diversion of material at bulk handling facilities, including at enrichment plants. First, material can be diverted into MUF.[49] This can be accomplished when physical inventory measurements yield a MUF variance large enough to allow for the undetected diversion of a given quantity of material. In this case, accounting records are not falsified, and the missing material forms part of the operator's declared MUF, which happens to be acceptably small relative to σ_{MUF}. The risk of diversion into MUF can be mitigated through the use of more accurate measurement methods, which decreases the MUF variance. Material can also be diverted into SRD,[50] again without falsifying data, but this path can also be made difficult with accurate measurement methods. Of course, in some cases, for example in large-scale gaseous diffusion plants or at large-scale reprocessing plants, both the observed MUF and σ_{MUF} can be

[49] International Atomic Energy Agency, *IAEA Safeguards Glossary: 2001 Edition*, 77.
[50] Ibid.

very large over a MBP, necessitating the use of special near-real-time-accountancy (NRTA) methods to ensure that material is not diverted into MUF or SRD.[51] An operator may also choose to falsify records so that missing material does not appear in MUF via diversion into $\widehat{D}$, the operator-inspector difference statistic, which as its name suggests, is calculated by comparing the results of inspection activities with declared operator data.

The $\widehat{D}$ statistic can be interpreted as the difference between the IAEA's estimated physical inventory with the operator's declared physical inventory. It can also be used as the estimate of the bias in MUF reported by an operator, under the assumption that measurements by the inspectorate are unbiased.[52] As defined in the IAEA Safeguards Technical Manual, $\widehat{D}$ is calculated at the stratum level for each component of the material balance equation (beginning physical inventory, inputs, outputs, and ending physical inventory), where for stratum k:

$$\widehat{D}_k = N_k \bar{d}_k \qquad (2.6)^{53}$$

A stratum is defined as "a grouping of items and/or batches having similar physical and chemical characteristics (e.g. isotopic composition) made for the purpose of facilitating statistical sampling."[54] Strata within the storage MBA at an enrichment facility, for example, are divided into feed cylinders containing natural uranium, tails cylinders containing DU, and product cylinders containing LEU. In equation 2.6, N_k is the number of items in the stratum, and $\bar{d}_k$ is the average

[51] S.J. Johnson et al., "Development of Safeguards Approach for the Rokkasho Reprocessing Plant," IAEA-SM-367/8/01, Proceedings of the 2001 IAEA Safeguards Symposium (Vienna: International Atomic Energy Agency, 2001).
[52] International Atomic Energy Agency. *Safeguards Technical Manual, Part F*, IAEA-TECDOC-261, 140.
[53] Equation 3.5.1, ibid.
[54] International Atomic Energy Agency, *IAEA Safeguards Glossary: 2001 Edition*, 53–54.

difference between the operator's declared value and the IAEA's measured value (i.e. mass of an element or isotope) for each item in the stratum. $\widehat{D}_k$ values are subsequently summed over all strata to calculate $\widehat{D}$:

$$\widehat{D} = \sum_k A_i \, \widehat{D}_k \qquad (2.7)^{55}$$

where $A_i = 1$ for flow inputs and beginning physical inventories in each stratum and $A_i = -1$ for flow outputs and ending physical inventories in each stratum. Thus, the $\widehat{D}$ statistic is effectively the estimated difference between the operator's and the inspectorate's calculation of MUF. However, should be noted (and is apparent from the definition of $\widehat{D}$) that the inspectorate need not verify every item in every stratum—instead, the inspectorate only needs to measure a sufficient number of items with sufficient accuracy such that the variance of $\widehat{D}$ is low enough to be sufficiently sensitive to discrepancies between operator and inspector flow and inventory data.

Calculating the variance of $\widehat{D}$, $V(\widehat{D})$, can involve complicated arithmetic. At the highest level, $V\left(\widehat{D}\right)$ can be broken down into the sum of variances due to random error, $V_r(\widehat{D})$, short-term systematic error, $V_g(\widehat{D})$ and long-term systematic error, $V_s(\widehat{D})$.[56] Short-term systematic error is typically used to describe differences in biases between the analytical laboratories to which inspectorates send samples for analysis, while long-term systematic error might arise from biases such as those associated with use of a certain measurement technique (that in this analogy would

[55] International Atomic Energy Agency. *Safeguards Technical Manual, Part F*, IAEA-TECDOC-261, 140.
[56] Ibid., 159.

be common to all laboratories).[57] Each of these three terms is the sum of the variance attributable to the operator's measurement techniques, and the inspectorate's measurement techniques.[58] Operator and inspector variance terms are calculated by propagating errors associated with measurements at each stratum, which are themselves calculated via error propagation from variance terms that arise from the number and type of measurements applied. This procedure is given in highly detailed form in the *IAEA Safeguards Technical Manual*.[59]

Once $V(\widehat{D})$ has been calculated, a hypothesis test can then be used to determine whether the true value of $\widehat{D}$ is non-zero. If $\widehat{D}$ is determined to be non-zero with sufficient confidence, this implies that the inspectorate has found a significant bias, or a discrepancy, in the operator's calculation of MUF that cannot be attributed to measurement uncertainties. In this case, it is possible that records have been falsified, i.e. that diversion into $\widehat{D}$ has taken place, and thus further investigation is warranted.

Inspectorates may also employ a third statistic, $MUF - \widehat{D}$, which is effectively an unbiased estimate of MUF, as calculated by the inspectorate. By equation 2.7, $\widehat{D}$ is designed so that it is positive when MUF is overstated by the operator, and $\widehat{D}$ is negative when MUF is understated. Thus, $MUF - \widehat{D}$ represents the inspector's estimate of MUF. The variance of $MUF - \widehat{D}$, $V(MUF - \widehat{D})$, can be calculated both for the mass of an element or isotope, and is given by

[57] Ibid., 10–14.
[58] Ibid., 152, 157.
[59] Ibid., 139–168.

$$V\left(MUF - \widehat{D}\right) = V\left(\widehat{D}\right) - V(MUF) + 2V_0 \qquad (2.8)^{60}$$

where V_0 is the portion of MUF variance due to systematic measurement errors that are common to both the facility and the inspectorate (given that many techniques, such as UF_6 cylinder weighing) are employed by both. Because it is necessary that

$$V\left(MUF - \widehat{D}\right) = V(MUF) + V\left(\widehat{D}\right) - 2cov(MUF, \widehat{D}) \qquad (2.9)$$

it follows that

$$cov\left(MUF, \widehat{D}\right) = V(MUF) - V_0 \qquad (2.10)^{61}$$

If hypothesis testing shows $MUF - \widehat{D}$ to be significantly different from zero, then this indicates the possibility of either diversion into MUF (i.e. material is indeed unaccounted for, and data were not falsified), or of diversion into $\widehat{D}$, as when an operator falsely understates MUF, then $\widehat{D}$ must be negative, and $MUF - \widehat{D}$ necessarily increases. The IAEA Safeguards Glossary notes that testing of $MUF - \widehat{D}$ actually yields a higher probability of detection than the $\widehat{D}$ statistic alone,[62] and this property is demonstrated numerically in the *IAEA Safeguards Technical Manual*.[63]

[60] Ibid., 171.
[61] Equation 3.6.6, ibid.
[62] International Atomic Energy Agency, *IAEA Safeguards Glossary: 2001 Edition*, 77.
[63] International Atomic Energy Agency. *Safeguards Technical Manual, Part F*, IAEA-TECDOC-261, 169; R. Avenhaus and H. Frick, "Statistical Analysis of Alternative Data Evaluation Schemes (The MUF-D Evaluation Problem)," First Annual Symposium on Safeguards and Nuclear Materials Management (ESARDA) (Brussels, 1979).

Finally, an operator may choose to artificially inflate the random error associated with MUF calculations, in order to increase the MUF (and $MUF - \widehat{D}$) variance, thereby lowering the probability of detecting a diversion. To counteract this possibility, an inspectorate can conduct a chi-square test, estimating the operator's random error variance (where the operator and inspectorate use common measurement techniques, systematic error variance should be identical), and comparing it to the expected random error variance of the PIT measurement techniques specified in facility design information.[64] In addition, the IAEA publishes a set of International Target Values (ITVs)[65] containing acceptable uncertainties associated with the measurement techniques used by facility operators, the IAEA, and Euratom. For example, the ITVs for a ^{235}U abundance measurement on DUF_6 in a UF_6 cylinder using an Inspector Multichannel Analyzer with a sodium iodide detector (IMCN) are a relative random standard error of 20%, a relative systematic standard error of 8%, which combine for a total relative standard error of 22%.[66]

Material Accountancy at GCEPs

The previous section established the basic principles that safeguards inspectorates use to verify nuclear material accountancy. This section discusses the application of these concepts to GCEP safeguards.

[64] David M. Gordon and Jonathan B. Sanborn, "International Safeguards at the Feed and Withdrawal Area of a Gas Centrifuge Uranium Enrichment Plant," BNL-27663, Proceedings of the American Nuclear Society Conference on Measurement Technology for Safeguards and Materials Control (Charleston, SC, 1979), 11.
[65] International Atomic Energy Agency, *International Target Values 2010 for Measurement Uncertainties in Safeguarding Nuclear Materials*, STR-368 (Vienna, November 2010).
[66] Ibid., 30.

GCEPs typically consist of two main areas: a storage area, and a process area. The storage area may be divided up into areas containing feed, product and tails for the facility. Natural feed and tails are typically kept in 48-inch diameter purpose-made steel cylinders (designated "48Y" cylinders), and product is kept in smaller 30-inch diameter "30B" cylinders. UF_6 is stored as a solid in these containers. Shipping and receiving operations take place in the storage area. Typical inbound shipments include full 48Y cylinders containing natural UF_6, as well as empty 30B cylinders. Outbound shipments include full 30B cylinders, and can also include empty 48Y cylinders, in cases where they are not used as receptacles for tails material, and 48Y cylinders filled with tails material being sent for disposition at a depleted UF_6 conversion facility.[67] At U.S. facilities, feed cylinders are usually stored for 1–2 months before their contents are fed into the enrichment process.[68] Cylinders filled with DU from tails are often kept onsite for a decade or more, prior to disposition of the material via conversion to oxide form.[69] Product cylinders are typically kept in storage for 15-45 days, before being filled.[70]

A generic GCEP process area consists of a feed and withdrawal (F/W) area, a cascade area, and a blending and sampling area. Large commercial facilities are often divided up into 'units,' which can function essentially as separate plants, each with their own F/W area, cascade halls, and supporting facilities. F/W areas contain heating boxes for feeding operations, and 'cold boxes' for withdrawing UF_6 from product and tails lines. In feeding operations, UF_6 cylinders are placed directly in the heating boxes, which sublime the material into a gas, which then passes through a

[67] Jessica L. White-Horton et al., "The Life Cycle of 30B and 48Y Cylinders," ORNL/TM-2011/522, (Oak Ridge National Laboratory, April 2012), 4.
[68] Ibid., 25.
[69] Ibid., 27.
[70] Ibid., 30.

purification system before entering a unit feed header, which passes through a pressure reduction station. Today, withdrawal is accomplished at Western facilities by directly desubliming product and tails UF_6 into chilled cylinders inside withdrawal cells. Historically, a different process was used, wherein product and tails material was collected in desublimers, which stored UF_6 as a solid. Cold traps and chemical traps were used to extract any residual UF_6 not collected in desublimers. Once full, the desublimers would then be heated, and their contents would subsequently be transferred into product and tails cylinders, either as a gas or as a liquid.[71]

UF_6 undergoes enrichment in centrifuges housed in the cascade area of the plant. Each centrifuge takes in feed through one line and produces two streams: a product stream slightly enriched in ^{235}U, and a tails stream slightly depleted in ^{235}U. Centrifuges are piped together in parallel to form 'stages,' which are collectively connected in series to form a cascade. Each stage is fed by a combination of the product of the stage below it, and the tails of the stage above it. The number of stages and the number of machines in each stage are essentially related to the throughput, intended range of output enrichments for the facility, the need to maintain constant flows through cascades during steady-state operation, and the general concept that mixing of unequal enrichments is undesirable, as it wastes separative work. In reality, however, the relationship between these parameters is quite complicated, and is discussed in detail in Chapter 8. A typical GCEP production unit contains between 6–12 cascades, which are all connected to feed, product, and tails headers for the unit. Cascades are connected to unit headers via their own feed, product and tails headers. The pressure of UF_6 in cascade headers is about an order of magnitude lower than the UF_6 pressure

[71] J. Michael Whitaker, "Uranium Enrichment Plant Characteristics – A Training Manual for the IAEA," ISPO-310/R1 (U.S. Program for Technical Assistance to IAEA Safeguards, 2005), 34.

in the unit header, prior to when it undergoes pressure reduction. The nominal pressure in the unit headers at contemporary GCEPs has been stated to be approximately 40 Torr.[72]

After being filled, product cylinders undergo homogenization, as the enrichment of material fed into cylinders may not be constant over time (resulting in nonhomogeneous enrichment levels within a single cylinder). This involves placing a cylinder into an autoclave where its contents are heated under pressure, forming liquid UF_6, which is then mixed via thermal convection within the cylinder.[73] The homogenization process takes about 8 hours for 30B cylinders and about 12 hours for 48Y cylinders.[74] Tails cylinders, however, may not necessarily undergo homogenization,[75] as their isotopic content, from the operator's perspective, is of marginal importance. Product UF_6 may also be blended to produce intermediate UF_6 enrichments (e.g. equal quantities of 3% and 5%-enriched material can be combined, for example, to produce 4%-enriched material), at the cost of the separative work involved with producing the higher enrichment level. This takes place at a blending station, where UF_6 in two containers is heated and fed into a third container, blending the two streams together. Solidification of UF_6, following homogenization, takes approximately 3 days for a 30B cylinder.[76] After this time, product cylinders can be moved back to the storage area, where they are held for verification, prior to shipping.

[72] J. Ely et al., "On-Line Enrichment Monitor (OLEM): Supporting Safeguards at Enrichment Facilities," E-poster presented at the 2014 IAEA Safeguards Symposium, (Vienna: International Atomic Energy Agency, 2014).
[73] Whitaker, "Uranium Enrichment Plant Characteristics…," 49.
[74] Ibid.
[75] L.E. Smith et al., "Enrichment Assay Methods for a UF_6 Cylinder Verification Station," IAEA-CN-184/125, Proceedings of the 2010 IAEA Safeguards Symposium (Vienna: International Atomic Energy Agency, 2010), 1.
[76] Whitaker, "Uranium Enrichment Plant Characteristics…," 51–52.

Before discussing specific safeguards measures for GCEPs, it is also important to introduce the concepts of *quantity* and *timeliness* components of *inspection goals*. These components, taken together, aim to serve the purpose of safeguards, which in the case of INFCIRC/153, is the "timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection."[77] Quantity and timeliness components depend upon the type of material under safeguards. At commercial GCEPs today, material accountancy verification concerns detecting the diversion of natural uranium (NU, containing 0.7% ^{235}U), depleted uranium (DU, containing <0.7% ^{235}U), and low enriched uranium (LEU, containing >0.7% and <20% ^{235}U),[78] as these are the materials present, as declared, in the facility's strata. For uranium enriched up to 20%, the IAEA's *inspection goal* is to detect the diversion of 75 kg of ^{235}U within one year (with the total amount of U diverted inversely related to material enrichment). This amount of material is known as a significant quantity (SQ), which is approximately related to the amount of material that precludes the exclusion of the possibility of manufacturing a nuclear explosive device.[79] One SQ is the quantity component of the inspection goal, and one year is the timeliness goal, which is based on the conversion time for the material, which is the IAEA's estimate of the time needed for converting <20% enriched uranium to metallic highly enriched uranium (HEU, containing ≥20% ^{235}U, but typically much more, around 90%, for use in weapons). For a conversion time of 3-12 months (on an "order of months") for NU, DU and LEU,[80] the IAEA sets a timeliness goal of 1 year.[81] To meet this inspection goal, material

[77] "The Structure and Content of Agreements…," INFCIRC/153 (corr.), para. 28.
[78] International Atomic Energy Agency, *IAEA Safeguards Glossary: 2001 Edition*, 23.
[79] Ibid.
[80] Ibid., 22.
[81] Ibid., 24–25.

accounting is performed both on the ^{235}U isotope, as well as on elemental uranium. Material balance closure for ^{235}U and elemental U, via PIT by the operator and physical inventory verification (PIV) by the inspectorate, takes place annually, in line with the timeliness goal. Inspectorates also perform interim inventory verification (IIV) visits that do not coincide with the closing of an MBP for the purpose of verifying the material flows between MBAs, as well as in and out of the plant (thereby verifying the operator's book inventory) and improving detection timeliness. During these visits, inspectorates use inventory verification tools used in PIV, but as 'spot checks' to determine that declared information is consistent with items that are present. IIV inspections are typically carried out on a monthly basis at commercial GCEPs, and GCEP operators customarily hold all incoming feed cylinders that arrived since the previous IIV, and all product and tails cylinders filled since the previous IIV for verification by the inspectorate.[82] In addition to quantity and timeliness goals, the detection probability targets are assigned. In 2008, it was reported that the IAEA's target detection probability for LEU diversion from GCEPs, given a quantity component of 75 kg of ^{235}U and a timeliness component of 1 year, was 50%.[83]

Accounting for elemental uranium is a matter of accounting for masses of UF_6 contained in items in each MBA throughout a plant. Using a draft facility Attachment for the E21, E22A and E22B plants at Capenhurst as a guide, a facility might be divided into a storage MBA, a process MBA containing UF_6 handling and cascade areas, and a blending/sampling MBA.[84] High-accuracy UF_6 cylinder accountancy scales equipped with gyroscopic load cells are typically located in cylinder

[82] Brian Boyer, "Safeguards Approaches for Gas Centrifuge Enrichment Plants," LA-UR-08-03736 (Los Alamos National Laboratory, July 1, 2008), 27.
[83] Ibid., 19.
[84] European Atomic Energy Community, "Safeguards Agreement in connection with NPT - Subsidiary Arrangements - Facility Attachment: QCAY," BArch, B 196/54363 (May 20, 1983).

storage areas. These scales can be accurate to as little as ±1 kg under a 20,000 kg load.[85] Containers are typically weighed by operators upon their arrival at the facility, after they are filled or emptied, or any material is removed from them for any reason (e.g. after sampling).[86] An operator may also place seals on cylinder valves after they have been weighed as a continuity of knowledge measure, that the previously recorded weight can be assumed to be valid at a later time, for example, during a physical inventory taking. During inspections, an inspectorate will also use the operator's accountancy scales, but will ensure their accuracy by performing a scale calibration with check weights.[87] In a PIV exercise, inspectors will verify that only cylinders identified in the operator's physical inventory are present (thus verifying the identity of each cylinder in the facility), and select cylinders at random for weighing to sufficiently minimize the variance of $\widehat{D}$. Cylinders that are declared to be empty may be verified via resonance testing, as empty cylinders should resonate when physically struck.[88]

In addition to verifying mass balance for elemental uranium, inspectorates must also verify the mass balance for the ^{235}U isotope. ^{235}U in GCEPs is measured and verified using both non-destructive assay (NDA) and destructive assay (DA) techniques. Enrichment plants typically feature an on-site analytical laboratory equipped with mass spectrometers, which measure the isotopic ratios in UF_6 samples with very high accuracy. Liquid UF_6 samples can be drawn immediately after homogenization has taken place, after which cylinders are allowed to cool and the UF_6 returns to solid form. Operators perform these measurements not only to account for ^{235}U,

[85] WÖHWA, "WÖHWA Gyroscopic Load Cell - High-accuracy weighing of heavy loads," accessed October 11, 2017. http://www.woehwa.com/produkte/kreisel/pdf/100721kreiselwaagen-en.pdf.
[86] Whitaker, "Uranium Enrichment Plant Characteristics…," 48.
[87] Whitaker, "Uranium Enrichment Plant Characteristics…," 48–49.
[88] H.C. Taylor and D.S. Williams, "Gas Centrifuge Plant Safeguards – An Operator's View," Proceedings of the 52nd Annual Meeting of the Institute of Nuclear Materials Management (Palm Desert, CA, 2011), 3.

but also for quality assurance and control purposes. Product samples are also shipped to customers along with product cylinders, allowing customers to independently verify the isotopic composition and purity of the material. A GCEP may also be equipped with on-line mass spectrometers directly connected to process piping, which may be used for process control. These mass spectrometers are typically less accurate than the laboratory devices, which form the basis of the operator's accounting system for ^{235}U, along with cylinder weighing.

Inspectorates also retrieve samples from UF_6 cylinders, or from process flows, during inventory verification activities. Cylinders are selected on the basis of a sampling plan devised to provide the necessary detection probability via sufficiently minimizing the variance of $\widehat{D}$ and $MUF - \widehat{D}$. If a cylinder has already been homogenized (as should be the case for product cylinders in storage), it may not be necessary to liquefy and homogenize the contents of the entire cylinder, and a gas-phase sample may be drawn instead. Gas-phase sampling accomplished by connecting a sampling vessel under vacuum to the cylinder. When the cylinder valve is opened, gaseous UF_6 is drawn into the sampling equipment. The bottom of the sampling vessel is cryogenically cooled, causing the UF_6 to solidify in the sampling vessel.[89] While this procedure is more time efficient than liquid phase UF_6 sampling, however, significant time and labor is needed for moving a cylinder from storage to a sampling station, preparing the required equipment, carrying out the sampling procedure, reweighing the cylinder, and moving it back to storage. Inspectorates are also limited by the physical capacity of the laboratories to which samples are sent for analysis. Thus, the number of cylinders that can be sampled during inventory verification is limited. During an annual

[89] ASTM International, "Standard Practice for Sampling of Gaseous Uranium Hexafluoride," C1703-08 (2013).

PIV at Capenhurst in the early 2010s, only 9 samples were taken from UF_6 cylinders over the 2-week duration of the exercise.[90]

Inspectorates supplement DA of UF_6 samples by carrying out NDA on UF_6 containers. Today, inspectors use sodium iodide detectors or electrically cooled sodium high-purity germanium detectors[91] to measure gamma spectra emitted by the cylinders. Enrichment values can be calculated via comparing the magnitude of the 186 keV peak from ^{235}U with the 1001 keV peak that results from ^{238}U decay, but this method is unreliable for measurements of large quantities of solid UF_6, because 186 keV photons are attenuated at far higher rates than 1001 keV photons within the material, and the physical profile of UF_6 within a cylinder is variable, thus making it difficult to disentangle the effects of enrichment and geometry on the measured gamma spectrum. The Multi-Group Analysis for Uranium (MGAU) method, by contrast, calculates enrichment by analyzing gamma and x-rays emitted from the decay of ^{235}U and ^{238}U between 84 and 130 keV, which are attenuated at similar rates.[92] This method allows for enrichment measurements up to 1-2% accuracy, although due to the low energy of the region of interest, cylinder wall thicknesses must be less than 10 mm to prevent excessive attenuation.[93] In this case, the analytical process is automated, and results for NDA on UF_6 cylinders can be obtained instantaneously. These

[90] Taylor and Williams, "Gas Centrifuge Plant Safeguards – An Operator's View," 5.
[91] Heather H. Erpenbeck et al., Practical Issues Associated with Implementing an Advanced Safeguards Approach at Gas Centrifuge Enrichment Facilities," Proceedings of the 53rd Annual Meeting of the Institute of Nuclear Materials Management (Orlando, FL, 2012), 3. See also International Atomic Energy Agency, "Safeguards Inspection of a Uranium Enrichment Plant," (Youtube, November 30, 2015). https://www.youtube.com/watch?v=Pf1MtMxnEEc.
[92] R. Gunnink et al., "MGAU: A New Analysis Code for Measuring U-235 Enrichments in Arbitrary Samples," UCRL-JC-114713 (Lawrence Livermore National Laboratory, 1994).
[93] International Atomic Energy Agency, *Safeguards Techniques and Equipment: 2011 Edition*, International Nuclear Verification Series No. 1 (Rev. 2) (Vienna: International Atomic Energy Agency, 2011), 13.

measurements can also be carried out relatively quickly: at the same Capenhurst PIV mentioned previously, inspectors conducted 749 NDA measurements.[94] Nevertheless, it must be emphasized that these gamma spectroscopy measurements are far less accurate than DA-based methods, and can be prone to biases—an enrichment calculation based on a gamma spectroscopy measurement at one end of a cylinder (particularly if it has not been homogenized) may yield different results from a measurement taken at the other end of the same cylinder. With a high number of measurements, combined with DA results, however, $V(\widehat{D})$ for ^{235}U can be reduced to an acceptable level.

Inspectorates may also apply tamper-indicating seals to UF_6 cylinders to maintain CoK on previously weighed or measured material. Seals are also commonly used to verify that safeguards equipment or information left at the facility is not tampered with.

Material accountancy verification activities at GCEPs, as should be clear from this section, take place primarily in UF_6 cylinder storage areas. Verifying the contained UF_6 masses and assays in feed and withdrawal areas is more difficult. First, containers connected to process piping are unidentifiable by inspectors, as they are housed in autoclaves and refrigerated cells, which cannot be opened safely in an instant, and thus must be verified at a later time. Cylinders that are staged in the feed and withdrawal area typically must to be moved elsewhere to be weighed or sampled, impacting facility operations. To simplify accounting in the process area, feed UF_6 cylinders connected to the plant are considered to be full until they are disconnected, and product and tails cylinders are considered to be empty until they are disconnected, so that the emptying and filling

[94] Taylor and Williams, "Gas Centrifuge Plant Safeguards – An Operator's View," 5.

of each cylinder only results in a single instantaneous inventory change.[95] Cascade hall inventories are generally neglected, as UF_6 in cascades is at a low pressure, and thus the total mass of material in cascades at any given time is very low. Furthermore, there exists no practical method for verifying the total in-process inventory of nuclear material in a single inspection visit.

Reflecting on Material Accountancy and Considering Misuse Scenarios

From the previous two sections it should be apparent that material accountancy, and its application at GCEPs, is a highly codified and regimented undertaking. Terminology including 'material unaccounted for,' 'material balance area,' 'inventory change,' 'key measurement point,' 'strategic point,' 'physical inventory,' 'book inventory,' 'batch,' and 'batch data' are defined explicitly in INFCIRC/153, and in every State's comprehensive safeguards agreement. The IAEA Safeguards Technical Manual features a 300-page volume[96] devoted to the statistical concepts and methods used by operators and inspectorates in evaluating declared data and inspection results. Because of this, the nature and aims of international safeguards have evolved over time, particularly over the last three decades, material accountancy has hardly changed in nature since the approval of INFCIRC/153 in 1972. Conceptually, the core of safeguards has remained the same: operators declare accountancy data to the inspectorate, which independently verifies the declared information using an approach explicitly spelled out in a safeguards agreement, and codified in official technical documentation.

[95] Interview with U.S. safeguards expert (August 2017).
[96] International Atomic Energy Agency. *Safeguards Technical Manual, Part F*, IAEA-TECDOC-261.

The application of material accountancy at GCEPs, as will be shown in the following four chapters, was not a controversial issue as stakeholders worked to devise a GCEP safeguards approach. As conversations on this issue began in the early 1970s, the goalposts for material accountancy had already been set, and it was clear that nearly all the verification effort in this realm would go towards verifying the non-diversion of UF_6 in storage areas, as well as UF_6 received by and shipped from the facility. Inspector access to cascade areas, which would become the epicenter of contentious discussions on GCEP safeguards, was generally a non-issue for material accountancy, owing to the small and largely unverifiable inventories of enrichment cascades.

To many stakeholders at the time, however, material accountancy did not address the entirety of the safeguards mission space for GCEPs. Unlike other nuclear fuel cycle facilities, GCEPs had the potential to be misused to produce unirradiated *direct-use material*—that is, nuclear material suitable for use in nuclear explosive devices without any further enrichment, or isotopic transmutation.[97] Cascades of centrifuges in a commercial GCEP, declared to be producing only LEU, could be rearranged or configured in series to produce HEU suitable for use in a nuclear weapon. Previously enriched material could also be re-fed through cascades in batches, achieving the same result.[98] Thus, to some, it made little sense only to employ the quantity and timeliness goals that applied to DU, NU and LEU (i.e. 75 kg of ^{235}U within 1 year), and to execute material accountancy under these standards, when the very same facility could produce weapons-usable material in weapons-usable quantities in far less time, which could be subsequently converted into

[97] International Atomic Energy Agency, *IAEA Safeguards Glossary: 2001 Edition*, 33.
[98] Alexander Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation," *Science and Global Security* 16, no. 1–2 (2008): 1–25.

weapons components in a matter of weeks.[99] The material accountancy timeliness goal of 1 year, for only 75 kg of LEU, in itself, would seem inadequate as a deterrent to *misuse*. It was abundantly clear at the time that commercial-scale facilities, with capacities on the order of thousands of tonne-SWU (tSWU) of separative work per year, could produce weapons-usable quantities of material in far less time than the 1-year timeliness criterion for LEU. If it was to be assumed that misuse of a GCEP was a credible scenario, then it would be necessary to consider a set of measures, in addition to material accountancy, that would detect this activity before HEU could be removed from the facility for conversion. Furthermore, there existed a possibility (which would be heavily disputed) that undeclared material could feature in a misuse scenario, either to produce HEU, or to produce LEU 'off the books' for clandestine enrichment elsewhere.

Verifying the Absence of Misuse

Guidelines for designing an effective approach for detecting GCEP misuse are (and were) not codified in the same way that material accountancy measures are. However, it is possible to establish a set of general principles that can be used to estimate the capabilities of such a system.

First, it is important to consider signatures of misuse (in particular, HEU production), and potential means for detecting these phenomena. The most obvious signature, of course, is the presence of material enriched beyond the maximum level declared in a facility's design information. Over-enriched material in cylinders could be deliberately concealed from inspectors and/or transported

[99] The IAEA Safeguards Glossary notes that the estimated "conversion time" for unirradiated HEU compounds (i.e. UF_6) is on the "order of weeks," or 1–3 weeks. This entails the time it would take to chemically convert UF_6 into metallic form, and then fabricate it into (a) weapon component(s). See International Atomic Energy Agency, *IAEA Safeguards Glossary: 2001 Edition*, 22.

from the facility or placed in declared storage areas (with the risk that the material could be discovered during an IIV or PIV). Given the fact that an SQ of HEU is only 25 kg of contained ^{235}U,[100] the former option is likely to be preferable in most scenarios. An SQ of 90%-enriched UF_6 weighs 41.3 kg and can be held safely in two "5B" cylinders, which are 5 inches in diameter, and about 36 inches in height. Nevertheless, other methods—in particular, environmental sampling and NDA—offer more potential for misuse detection. Uranium-containing particles may be released into the facility during a misuse episode, particularly as cylinders are connected and disconnected from the product line. Environmental swipe sampling, which only became available to the IAEA from the early 1990s onwards, offers a means for measuring the enrichment of the uranium in these particles. Results from this procedure, while highly accurate and precise, usually take on the order of weeks to obtain, thus may not be wholly sufficient for timely detection.

NDA methods deployed in process areas, many of which are discussed later in this dissertation, provide timelier, although less precise means for detecting misuse. A vast array of systems has been proposed, some intended for unattended operation (some of which allow for remote monitoring from inspectorate headquarters locations) and others for manned use, some relying on neutron emission measurements and others on gamma spectroscopy, and some intended for measurements at specific points (e.g. cascade or unit headers), and others for aggregate radiation measurements from entire cascade halls—but as later chapters in this dissertation will show, only a handful of these systems have ever been used to effect by inspectorates.

[100] International Atomic Energy Agency, *IAEA Safeguards Glossary: 2001 Edition*, 23.

During misuse episodes, flow rates of UF_6 in process areas may deviate from usual values, particularly if cascades within a unit are rearranged from being in parallel to being in series with each other. Flow monitors on header piping could be used to detect these changes, although they may reveal sensitive information about cascade technology to inspectorates and have not been used for safeguards to date. In any case, if flow monitors were to be used, they would have to be installed in such a way to preclude breaching the integrity of any header pipes. Verification of data simultaneously taken from the facility-operated load cells installed inside F/W cells would also provide a detection capability, although this information could be prone to spoofing.[101]

Visual inspection of process areas may also uncover evidence of misuse. Some GCEPs, including Urenco plants designed prior to the late 1980s/early 1990s, contain visible features on process piping that may be viewed by inspectors to verify the absence of cascade reconfigurations at the plant. Other designs, however, likely including more recent Urenco plants, feature internal valves that are remotely manipulated, leaving no direct visual signature of reconfiguration. Other signs may exist, however: the presence of mobile feed and withdrawal carts in cascade areas, along with cylinders suitable for carrying HEU, might be indicative of an imminent, current, or recent misuse episode.

It is possible to conceptualize a system for verifying the absence of misuse that relies primarily on unattended, remotely monitored NDA and flow measurement technologies, supported by prompt

[101] Load cell monitoring has also been proposed in a different context as a means for making PIV and IIV more efficient, as load cell mass data can be used for operator physical inventory declarations, as well as for flow declarations, ahead of IIV. See P. Richir et al., "Development and Functionalities of a Software Tool to Perform the Monitoring for Safeguards Activities of Gas Centrifuge Enrichment Plants Making Use of Load Cell, Accountancy Scale and On-line Mass Spectrometer Plant Data," Proceedings of the 58th Annual Meeting of the Institute of Nuclear Materials Management (Indian Wells, CA, 2017).

in-person inspection activities if these systems indicate abnormal conditions that could indicate HEU production. The primary advantage of such a system would be that it would allow for highly timely (essentially real-time) verification of the absence of misuse. Considerable downsides exist, nevertheless. To rely entirely on unattended systems to cue on-site activities would require use of a combination of monitoring devices that would comprehensively cover every path towards misuse, leading to an expensive, byzantine operation. Each of these devices would also need to meet a very high standard of reliability, and feature an extremely false alarm rate, possibly at the expense of detection probability. In the early days of GCEP safeguards in the 1980s and 1990s, unattended systems were not available for GCEP safeguards. Thus, at the time, on-site inspection was the only viable verification option.

Through the early 1980s, however, discussions over the nature of on-site inspection activities for misuse detection were extremely controversial. The next four chapters cover these issues in granular detail. At this stage, however, it is useful to introduce basic concepts that undergird random on-site inspections, without going into specific measures. First it must be noted that scheduled inspections at known times, particularly with regular intervals, do not provide a sufficient deterrent against misuse, if weapons-usable quantities can be produced and diverted, and signatures of the activity removed, within the known intervals. Thus, random inspections are preferable. Inspection frequency is of fundamental importance. It can be defined in two ways: as a numerical limit within a certain time interval (i.e. a maximum of 12 inspections per calendar year on randomly selected dates), or as an average number of inspections in a time interval. Inspection scheduling under the latter concept, for example, for an average of 12 inspections per year might involve setting the time interval between inspections to a normally distributed random variable

with a mean of 1 month, and a given variance, and then selecting individual instances of this variable. Use of an average inspection frequency, instead of a hard limit, provides a stronger deterrent effect, as this eliminates the ability of the operator to strategically choose when to misuse a facility: if the maximum number of inspections in a calendar year is set to 12, and all twelve inspections have already taken place by November 15, then the operator will know that no inspections will take place in the final six weeks of the year, and may behave accordingly. Use of the average frequency approach eliminates this possibility.

The rate at which misuse can potentially take place is also of great consequence in evaluating a safeguards system for detecting misuse. The term 'breakout time' can be used to describe the minimum time required for an enrichment plant to be reconfigured for producing HEU at weapons-usable levels, and then to produce a weapons-usable quantity (i.e. an SQ) of material.[102] The simplest and roughest way of calculating breakout time would be to take the separative work required for producing an SQ of 90%-enriched material (about 5000 kgSWU starting from natural feed, or about 1500 kgSWU starting from 5%-enriched feed, depending on the enrichment of the tails from the process), and dividing it by the plant's separative capacity per unit time. However, this method ignores several practical constraints, in particular, the time required for reconfiguring the plant, and whether the necessary feed for the activity is available. About 800 kg of 5%-enriched UF_6, for example, would be needed to produce an SQ of 90%-enriched UF_6, if an actor were to choose this option. Furthermore, the division of plants into units and individual cascades precludes an operator from piping the whole plant together in the most efficient way possible (without

[102] Another definition for 'breakout time' is the minimum time required for a State or an actor to produce a deliverable nuclear weapon, which goes beyond the mere production of weapons-usable fissile material. In this dissertation, the former definition is used.

actually re-plumbing the entire plant, which would take an unrealistic amount of effort). Chapter 8 examines this issue further, and demonstrates that this constraint, implemented in a generic model facility constructed using reasonable assumptions, can increase the estimated breakout time by at least a factor of two.

Given some assumptions about breakout times and inspection frequencies, it is possible to create a very simple model to estimate the overall detection probability associated with a given inspection frequency, within a given year, with respect to the amount of time per year that a GCEP is used maliciously. The time during which misuse is occurring is assumed to include the time it takes to reconfigure the plant for HEU production, as well as the time required for removing evidence after production has taken place (and ignores the possibility of swipe samples revealing the presence of HEU in the facility at a much later date). The duration of misuse depends both on the amount of material that the operator intends to produce, as well as the capacity of the plant being dedicated to that purpose. For the following example, however, it can be assumed that an operator desires to misuse a facility for x days out of the year. In this case, x could be considered to be a plant's 'breakout time.' At this stage, it can also be assumed that on-site inspections incur no false negatives (i.e. they have a 100% detection probability). If inspections take place on s days within a given amount of time t, then the overall detection probability P is given by the simple expression:

$$P = 1 - \left(1 - \frac{x}{t}\right)^{s}, \qquad s \leq t \tag{2.11}$$

This model does not faithfully reflect reality—a significant inaccuracy emerges when s approaches t, where it becomes probable that inspectors 'select' the same day more than once. Furthermore, it

also assumes that regularly scheduled verification activities within the interval *t* have zero chance of detecting misuse, which not fully correct. Nevertheless, some intuition can be drawn from the model.

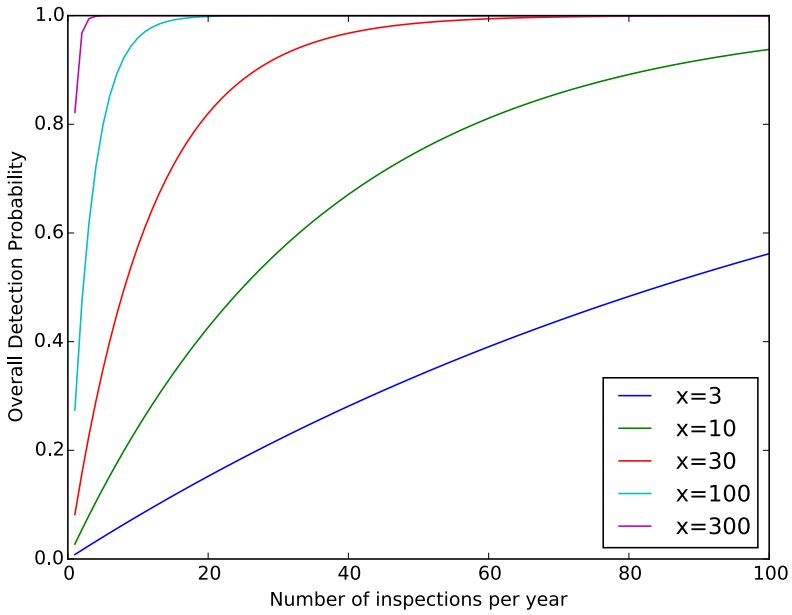

Figure 2-1: Evaluated overall detection probabilities versus inspection frequency using equation 2.11. Here *t*=365 (one year).

Figure 2-1 displays overall detection probabilities over a period of one year, calculated using equation 2.11, in instances where an operator misuses a plant 3 days, 10 days, 30 days, 100 days, and 300 days out of a year. It is clear from Figure 2-1 that if an inspectorate would have reason to believe that an operator would require most of a year to produce a significant quantity of material at a GCEP (this would be typical of a pilot or research facility), there is no need for more than a handful of random inspections per year—in the case of $x = 300$, three random inspections per year already give a detection probability of over 99%. As the period required for consequential misuse shortens, however, detection probabilities fall dramatically. Where a potential misuse episode is estimated to require one month out of a year, achieving an 80% detection probability requires 19 inspections a year, while achieving a 50% detection probability requires 9 inspections per year.

Nevertheless, a 20% detection probability (which could prove to be a sufficient deterrent for some actors) can be achieved with only 3 inspections per year. In cases where misuse could take place in as few as 3 days within a year, however, detection probabilities plummet further. Even achieving a 20% detection probability in this case requires 28 visits per year, and a 50% probability requires 84 inspections per year, demanding excessive resources. Finally, an important insight is that if x is conceived as a breakout time, if measures are taken to increase this period from 3 days to 10 days, this allows for a large reduction in inspection frequency, as well as the detection probability that is practically attainable. For a 20% detection probability, moving from x = 3 days to x = 10 days reduces the number of necessary inspections from 28 to just 9 per year. Additionally, the number of visits required for a 50% detection probability from a highly costly 84 inspections/year to 25 inspections/year, or about one every two weeks.

Of course, the false negative rate during each inspection is unlikely to be zero in reality. In this case, we can modify equation (2.11) to feature a false negative rate β:

$$P = 1 - \sum_{i=0}^{s} \binom{s}{i} \left(1 - \frac{x}{t}\right)^{s-i} \left(\frac{\beta x}{t}\right)^{i}, \qquad s \leq t \tag{2.12a}$$

or

$$P = 1 - \left(1 - \frac{(1-\beta)x}{t}\right)^{s}, \qquad s \leq t \tag{2.12b}$$

In this case, we consider every combination of events in which the inspectorate chooses a day where misuse is not taking place, and also when an inspection does take place, but a false negative occurs. Here, the overall detection probability is equal to one minus the probability that no

detections occur over all inspections, but now there are multiple ways no detections can happen: all inspections may only take place on days on which no malicious activity is taking place, or all inspections may happen to be on days when misuse is taking place but a false negative occurs each time, or combinations of the two outcomes may occur with s choose i possible permutations, where i is the number of inspections during a misuse episode that result in a false negative. Equation 2.12a expresses this phenomenon and reduces by the binomial theorem to Equation 2.12b. Plots illustrating overall detection probabilities for where β equals 0.05, 0.1, 0.2 and 0.5 are given in Figure 2-2.

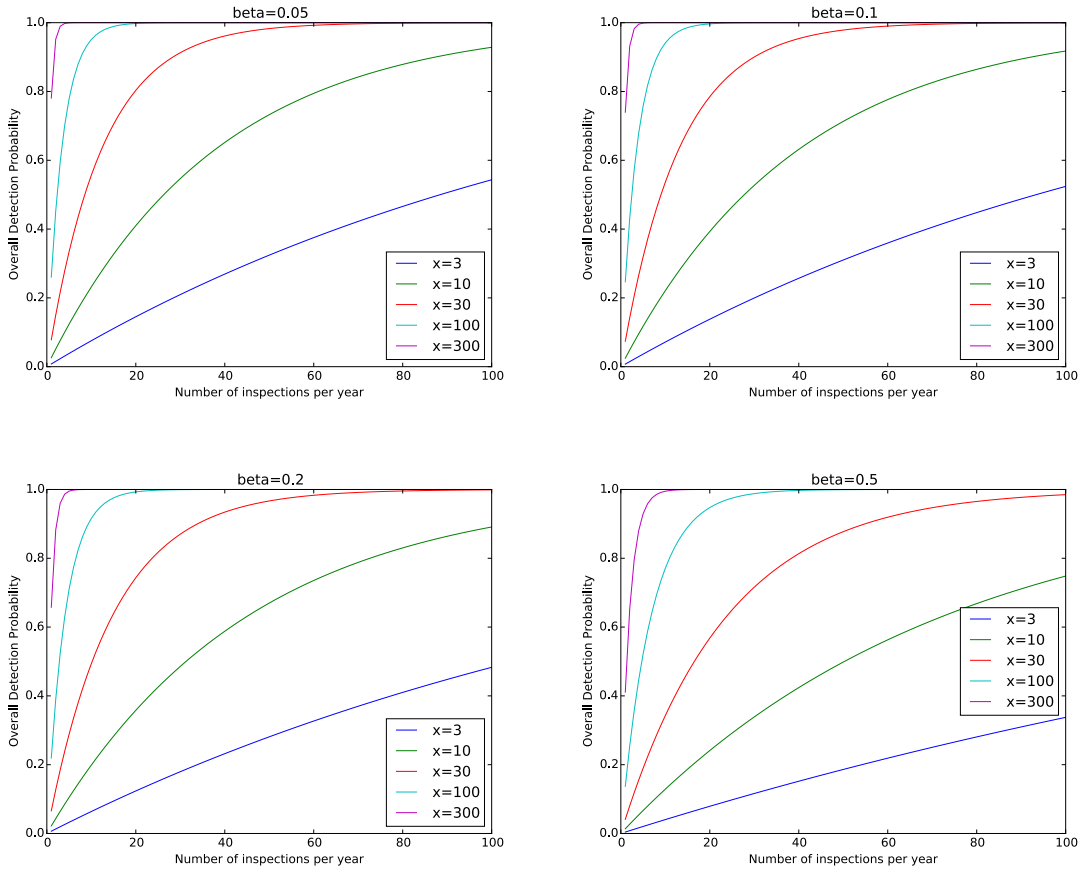

Figure 2-2: Evaluated overall detection probabilities versus inspection frequency using equation 2.12, using false negative rates of 0.05, 0.1, 0.2, and 0.5. As before, $t = 365$.

The effect of a change in the false negative rate β on overall detection probability depends on the level of confidence desired, and the estimated duration of a period of misuse. Table 2-1 shows the

necessary number of inspections for 20%, 50%, and 80% detection probability, versus β and x. If more than 100 inspections per year are required for a given detection probability, '>100' is used to indicate this condition. It is evident that the number of inspections required varies linearly with respect to the false positive rate. Because the requisite inspection frequency for plants with long 'breakout times' (e.g. x is between 3 months and a year) is so low in cases where the false negative rate is zero, the effect of higher false negative rates, in terms of additional inspections per year, is minimal, and the absolute number of inspections per year, even in cases where β=0.5, remains relatively low. In cases where the number of required inspections, given a zero false negative rate, is higher (i.e. when breakout times are short), changes to the false negative rate can have a more significant effect on inspection frequency. The implication of these observations is that high false negative rates can be acceptable for long breakout times and can be compensated by a few additional inspections, while a high β for GCEPs with short breakout times may precipitate a need for potentially untenable levels of inspection effort, particularly if higher confidence levels are desired.

Table 2-1: Necessary annual inspection frequency for attaining 20%, 50%, and 80% detection probability, against the number of days per year misuse is taking place (x) and false negative rate for inspections (β).

P = 20%		β				
		0	**0.05**	**0.1**	**0.2**	**0.5**
x	**3**	28	29	31	34	55
	10	9	9	9	11	17
	30	3	3	3	4	6
	100	1	1	1	1	2
	300	1	1	1	1	1

P = 50%		β				
		0	**0.05**	**0.1**	**0.2**	**0.5**
	3	84	89	94	>100	>100
	10	25	27	28	32	51
x	**30**	9	9	10	11	17
	100	3	3	3	3	5
	300	1	1	1	1	2

P = 80%		β				
		0	**0.05**	**0.1**	**0.2**	**0.5**
	3	>100	>100	>100	>100	>100
	10	58	62	65	73	>100
x	**30**	19	20	21	24	39
	100	6	6	6	7	11
	300	1	2	2	2	4

Verifying the Absence of LEU Production Using Undeclared Feed

Inspectorate use of NDA, flow measurements, and visual inspection of process piping rely on signatures of HEU production. These techniques do not allow of detection of misuse involving the production of undeclared LEU, at or below declared product enrichment levels, from undeclared feed, which constitutes another type of GCEP misuse. Undeclared LEU product, if produced, can be transported to a clandestine enrichment facility for further enrichment to weapons-usable levels, or to fuel a clandestine plutonium production reactor. On the basis of SWU capacity, a clandestine enrichment plant for HEU production would only need to be roughly one third of the size of a

clandestine plant fed by natural uranium, allowing for a smaller footprint and easier concealment of the facility.

Basic material accountancy techniques could detect undeclared feed or product cylinders if an operator were to hide them in plain sight in declared storage areas. Additional measures, however, are sufficient for detecting undeclared feed and LEU in concealed areas. Complementary access for inspectors to any location on a site, as provided for by the AP, could be useful in this regard. Nevertheless, a bottleneck in undeclared LEU production is the introduction of undeclared natural feed into the enrichment process. If an inspectorate has the capability to verify that no undeclared feed in locations other than the F/W area (including the cascade hall, via cascade access), verifying the absence of undeclared feed in the F/W area becomes useful. As mentioned earlier in this chapter, though, it is impossible for an inspector in a single visit to identify a cylinder currently being fed, as feed cells in service cannot be opened in an instant. The use of high frequency 'mailbox' declarations, coupled with unannounced inspections to the F/W area, can mitigate this problem. Mailbox declarations, transmitted electronically to inspectorates, are made by the facility operator, separate to material accountancy declarations, and can be made as frequently as every day.[103] If information on the identities of feed and/or product containers loaded in F/W cells is provided in a mailbox declaration, inspectors can make unannounced inspections to the F/W area, with the day's declaration in hand. Although the cylinders inside F/W cells are inaccessible at the time of this visit, inspectors can seal a fraction of operating F/W cells,[104] which can then be opened in the presence of an inspector at a later time, once feeding or product withdrawal has been

[103] P.J. Friend, "Field Trial of Mailbox Concept at a Urenco Enrichment Plant," Proceedings of the 49th Annual Meeting of the Institute of Nuclear Materials Management (Nashville, TN, 2008).
[104] Ibid., 2.

completed. Once the F/W cells are opened, inspectors can then verify the identity of the containers, and that it matches the mailbox declaration.

The Problem of Misuse

Today, IAEA safeguards activities at enrichment facilities seek to achieve three objectives that address the safeguards-relevant scenarios discussed above, as quoted from a 2007 IAEA GCEP safeguards concept paper:

> "(i) the diversion of nuclear material from the declared nuclear material flows and inventories; (ii) facility misuse to produce undeclared UF6 product at the declared product enrichment levels from undeclared feed (referred to as 'excess production'); and (iii) facility misuse to produce UF6 at enrichments above the declared maximum, in particular HEU."[105]

While these objectives are universally accepted among technology holders and inspectorates today, the necessity and means for verifying the absence of the latter two scenarios—both constituting facility misuse—were hotly disputed as discussions on developing the first GCEP safeguards approach took place. At the time, guidelines for material accountancy and the role of inspectorates in verifying the absence of nuclear material diversion had been well established. A

[105] Jill N. Cooley et al., "Model Safeguards Approach and Innovative Techniques Implemented by the IAEA at Gas Centrifuge Enrichment Plants," Proceedings of the 48th Annual Meeting of the Institute of Nuclear Materials Management (Tucson, AZ, 2007), 2.

completely different situation existed regarding the possible presence of misuse, as well as verification of its absence.

Some technology holders argued it was improbable that GCEP misuse would take place in States that had already committed themselves to nuclear nonproliferation by signing on to the NPT as NNWS and submitting to safeguards. Additional arguments were that material accountancy (although it only explicitly addressed the first scenario) would address all three objectives, as they all would involve the diversion of nuclear material that was obligated to be under safeguards, or that international safeguards (limited to material accountancy) was a single component of the wider nonproliferation regime, and that facility misuse and undeclared material could be detected via means other than safeguards activities. Unlike for material accountancy, no terminology and methodology for detecting misuse existed in the safeguards literature. Disputes over means for detecting misuse among technology holders, and between technology holders and inspectorates would drag on for over a decade, with politicization persisting throughout initial talks in the early 1970s up to the conclusion of the HSP in 1983.

The controversy over measures for GCEP misuse verification, however, is not only attributable to the non-explicit legal basis for safeguards activities beyond material accountancy. Other factors came into play. Demands by technology holders to prevent the dissemination of commercially and security-sensitive information would massively complicate the design of safeguards concepts in the early 1970s, and in the late 1970s and early 1980s, the same issue dominated discussions over inspector access to cascade areas, which house the most sensitive technology in a GCEP. As multilateral engagement on GCEP safeguards got underway, the IAEA, ill-equipped with technical

knowledge on GCEPs, was led by technology holders to make commitments on GCEP safeguards (most notably on cascade access) that it would later try to reverse under massive resistance by the same technology holders, when equipped with more information. Meanwhile, an antagonistic relationship developed in the early 1970s between Euratom and its Member States, as Euratom aggressively pursued cascade access under its own legal authority. These deep-seated differences precluded States from agreeing on a highly regimented system, akin to material accountancy verification, for addressing GCEP misuse. Instead, tools for detecting GCEP misuse were largely addressed through political compromise, instead of on the basis of concrete detection probability goals or effectiveness metrics, given the ostensible quantity and timeliness components for safeguards on LEU and HEU.

This dissertation aims, for the first time, to track the tortuous development of GCEP safeguards to the present day. Beyond this goal, however, this dissertation also seeks to examine how these roadblocks emerged, how they were resolved, and to draw lessons from past experiences so that today's efforts to improve the effectiveness and efficiency of GCEP safeguards can proceed without the dysfunction that hampered early GCEP safeguards development work. This analysis begins in the next chapter, which charts the course of GCEP safeguards through 1971, prior to the commencement of formal multilateral engagement on the topic.

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Chapter 3 – Laying the Groundwork for Gas Centrifuge Enrichment Plant Safeguards, 1945-1971

Although uranium enrichment had played a key role in the nuclear fuel cycle ever since the Manhattan Project, international safeguards on this process were not considered in depth until the early 1970s. However, by the time uranium enrichment safeguards became a topical issue, political conditions for producing an effective GCEP safeguards approach were far from ideal. Initial conversations on GCEP safeguards in the 1970s took place in an environment in which even the closest allies were unable to have candid technical discussions on the matter, setting up conditions for clashes over competing misuse verification visions when multilateral engagement began. In addition, the introduction of tight classification policies in the United States and Europe added to the challenge of designing an effective safeguards regime, while IAEA expertise on the issue lagged behind that of the technology holders. Ultimately, these conditions would lead to an environment in which political compromise steered stakeholders towards an agreed approach for misuse verification, over technically motivated goals. This chapter discusses how these conditions came to be.

The Beginning: Enriched Uranium for All, Uranium Enrichment for Nuclear Weapon States, Uranium Enrichment Safeguards for None

On the morning of August 6, 1945, an American B-29 bomber released the 'Little Boy' weapon over the city of Hiroshima, Japan. This attack, as estimated in 1946 by the Manhattan Engineer District of the United States Army, resulted in 66,000 deaths, 69,000 injuries, and the devastation

of more than four square miles of the city.[1] The use of this weapon, a bomb named "Little Boy," marked the first-ever detonation of a uranium-based nuclear weapon, as well as the second terrestrial nuclear explosion in history, the first having been the test of a plutonium-based device in a then-secret test in New Mexico, earlier that summer. The physical design of the "Little Boy" device was simple in comparison to contemporary implosion-type devices. Because highly enriched uranium (HEU) undergoes spontaneous fission at a lower rate than weapons-grade plutonium,[2] uranium-based weapons designs can be of the gun-type design, whereas plutonium-based weapons cannot.[3] "Little Boy" was a gun-type weapon that used HEU as its fissile material.

The material used in "Little Boy" was produced in absolute secrecy at facilities in Oak Ridge, Tennessee, a closed town built by the United States Government during World War II as part of the Manhattan Project atomic weapons effort. Two different techniques were used for uranium enrichment at Oak Ridge: gaseous diffusion was undertaken at a massive facility known as the K-25 plant, and electromagnetic isotopic separation (EMIS) was conducted at a separate facility, Y-12. Secrecy conditions were so strict that only a handful of the 75,000 residents in Oak Ridge even knew the nature of the work that they were doing.[4] These workers only discovered that they had

[1] The Manhattan Engineer District, *The Atomic Bombings of Hiroshima and Nagasaki,* ed. David B. Parker (June 29, 1946). http://www.gutenberg.org/files/685/685.txt.

[2] Spontaneous neutron emission in plutonium is driven by the material's ^{240}Pu content, which has a far greater spontaneous fission rate than the ^{239}Pu isotope. The United States defines weapons-grade plutonium as material that is less than 7% ^{240}Pu. See U.S. National Nuclear Security Administration, *The United States Plutonium Balance, 1944-2009*, DOE/DP-0137 (June 2012), 9.

[3] During assembly (detonation) of a hypothetical plutonium gun-type weapon, neutrons generated through spontaneous fission would most likely initiate a fission chain reaction at some point before desired maximum criticality of the weapon, resulting in the weapon blowing itself apart before full assembly of the weapon, resulting in a yield far less than intended—i.e., a fizzle.

[4] Many accounts of life in Manhattan Project cities during World War II are now available in popular literature – see, for example, Denise Kiernan, *The Girls of Atomic City: The Untold Story of the Women Who Helped Win World War II* (New York: Touchstone, 2013); Hill Williams, *Made in Hanford: The Bomb That Changed the World* (Pullman, WA: Washington State University Press, 2011).

been producing fissile material for nuclear weapons on the day of the Hiroshima bombing, on which President Harry Truman made a public statement, announcing that the United States had successfully produced nuclear weapons, and crediting workers at Manhattan Project sites at Oak Ridge, TN, Richland, WA, and Los Alamos, NM.[5] To foreshadow things to come, however, Truman also mused on the potential for the peaceful uses of nuclear energy in the same speech, in particular, recommending that Congress consider establishing "an appropriate commission to control the production and use of atomic power within the United States."[6]

From the summer of 1945 onwards, the potential benefits of generating electricity cheaply using atomic power stimulated substantial research efforts, eventually birthing a global commercial civil nuclear fuel cycle industry. But in the earliest days, the specter of non-peaceful uses of nuclear technology loomed large among policymakers. In fact, the very first resolution in the first ever session of the United Nations (UN) General Assembly established a UN Atomic Energy Commission (UNAEC), with the purposes of facilitating exchange of scientific information, controlling atomic energy to ensure that it was used only for peaceful purposes, to facilitate eliminating nuclear weapons from national armaments, and establishing safeguards to verify compliance with applicable agreements.[7] In anticipation of the creation of the UNAEC, the U.S. government commissioned a study on how such an international organization might implement safeguards for the purpose of verifying the peaceful use of nuclear technology. This study,

[5] Harry S. Truman, "Announcing the Bombing of Hiroshima," Harry S. Truman Presidential Library, Papers of Eben A. Ayers, "Army press notes," box 4 (August 6, 1945). Published online by *American Experience*, PBS, https://web.archive.org/web/20160507120922/http://www.pbs.org:80/wgbh/americanexperience/features/primary-resources/truman-hiroshima.
[6] Ibid.
[7] United Nations General Assembly, "Establishment of a Commission to Deal with the Problems Raised by the Discovery of Atomic Energy," Resolution 1 (I) (January 24, 1946).

commissioned by Under Secretary of State Dean Acheson, was undertaken from January through March 1946 by a board of consultants chaired by David Lilienthal, chairman of the Tennessee Valley Authority. The group's final report, known informally as the Acheson-Lilienthal Report,[8] would produce conclusions that would act as goalposts in early nuclear nonproliferation policymaking.

Although the authors of the Acheson-Lilienthal Report recognized that mankind was within "close reach" of achieving some of the potential benefits to be had from nuclear technology,[9] the report also acknowledged that the development of peaceful uses of nuclear energy and the development of nuclear weapons "are in much of their course interchangeable and interdependent."[10] This conclusion was based on the observation that certain nuclear fuel cycle processes, in particular uranium enrichment and spent fuel reprocessing, were common to both the production of fissile material for weapons, and the production of nuclear fuel for civil purposes. Acquisition of uranium ore was also identified as a step common to both peaceful and non-peaceful uses of nuclear energy.[11] Other steps in the peaceful nuclear fuel cycle, however, could be identified as "safe," as they would not assist a State in making any progress towards acquiring a nuclear weapon. Examples of "safe" activities included the use of radioactive materials as tracers, or the operation of low-power research reactors containing small quantities of fissile material.[12] These activities, according to the authors of the Acheson-Lilienthal Report, could be undertaken by individual

[8] U.S. Department of State, *A Report on the International Control of Atomic Energy*, Publication 2498 (Washington: U.S. Government Printing Office, March 16, 1946).
[9] Ibid., 17.
[10] Ibid., 4.
[11] Ibid., 22.
[12] Ibid., 27.

countries, under a "minimum of inspection" by an international authority.[13] Nuclear fuel cycle steps common to weapons and civil uses, however, were deemed to be "intrinsically dangerous" to such an extent that no system of safeguards or inspection could guarantee their use only for peaceful purposes, if technology for these activities remained in the possession of individual States.[14] Instead, the report recommended that an international agency be solely responsible for both technology development and operation of these activities, thus eliminating the ability of individual countries to carry them out. Furthermore, giving the international agency the sole right to develop sensitive nuclear technologies (as opposed to the agency merely being an inspectorate) would prevent nations from developing and using proliferation-sensitive technologies of value unbeknownst to the international agency. The authors of the Acheson-Lilienthal Report also noted technical problems that would impede a control system based solely on inspection of national facilities. Gaseous diffusion plants, which became the means of choice for uranium enrichment at the time, were thought to require a force of 300 inspectors, largely owing to the gargantuan scale of such a typical installation but also to monitor the activities of current and former staff. Inspectors would be capable of learning industrial secrets while at the facility. The day-to-day efforts of these inspectors, which would essentially be to verify the absence of bad faith by a plant operator, were deemed to be extremely dreary for the inspectors, and "obnoxious" from the perspective of a facility operator, who would be over-encumbered by intrusive inspection activities.[15] Furthermore, it was surmised that nations, upon official questioning of their activities by an inspectorate, might be tempted to bribe or coerce inspectors.[16] In short, therefore, the operation of nuclear fuel cycle

[13] Ibid., 31.
[14] Ibid., 21.
[15] Ibid., 7.
[16] Ibid.

activities common to peaceful and weapons uses (enrichment being one of them) under international inspection was thought to be doomed to failure.

A report published by the UNAEC[17] later in 1946 came to similar conclusions, while elaborating even further on technical issues concerning effective and efficient inspection activities at enrichment facilities, which at the time included gaseous diffusion plants (GDPs) and EMIS facilities. In particular, the report found that obtaining a material balance at enrichment plants at the time was "not possible," owing to their size, the amount of material contained in them.[18] In addition to this conclusion, this paper argued in line with the Acheson-Lilienthal report that control of enrichment plants must be in the hands of an international agency, and not by a national or private authority. Even if material balance uncertainties could be sufficiently improved, "the inherent danger of the operation"[19] would necessitate international control.

Such an international organization never materialized. Although the United States made a proposal in June 1946 to the UNAEC, known as the Baruch Plan,[20] to establish an International Atomic Development Authority (IADA) in the frame of the international agency envisioned in the Acheson-Lilienthal report, the plan was never adopted. Following the first test of a nuclear weapon by the Soviet Union in August 1949, prospects for outlawing possession of nuclear weapons and

[17] United Nations Atomic Energy Commission, "First Report of the Atomic Energy Commission to the Security Council," Working Committee for the Consideration of the Atomic Energy Commission (30 December 1946), reproduced in *Bulletin of the Atomic Scientists* 3, no. 1 (1947): 16–27.
[18] Ibid., 24.
[19] Ibid.
[20] Bernard Baruch, "The Baruch Plan: Statement by the United States Representative (Baruch) to the United Nations Atomic Energy Commission, June 14, 1946," reproduced in U.S. Department of State, *Documents on Disarmament*, 1945–1959. Vol. 1. 1945–1956 (Washington, August 1960): 7–16.

establishing an international agency for operating nuclear fuel cycle technology disappeared almost entirely.

The international organization that did emerge was the International Atomic Energy Agency (IAEA), which was chartered in 1957, furthering an initiative by a United States effort to export nuclear fuel cycle technology under safeguards, launched by President Dwight Eisenhower's "Atoms for Peace" speech to the UN General Assembly in December 1953.[21] Although the IAEA was not to operate any nuclear fuel cycle facilities itself, the Statute of the IAEA gave it the authority to apply safeguards to any technology transfer projects it facilitated, as well as to any other arrangements, upon request by one of its Member States.[22] For example, in the early days of the IAEA, a State exporting a research reactor along with fuel to a second State might request the application of IAEA safeguards on the reactor fuel, to provide assurance that it was being used for its intended purpose. A staff of inspectors would carry out the IAEA' safeguards obligations. IAEA safeguards activities under the Treaty on the Nonproliferation of Nuclear Weapons (NPT), of course, would not arrive until much later, in the 1970s.

The European Atomic Energy Community (Euratom), also emerged during this period. Euratom was originally conceived as a means for fostering further European integration through the collaborative development of nuclear fuel cycle technology, in a similar spirit to the economic

[21] Dwight D. Eisenhower, "Atoms for Peace Speech," (Vienna: International Atomic Energy Agency, December 8, 1953), accessed March 9, 2018, https://www.iaea.org/about/history/atoms-for-peace-speech.
[22] International Atomic Energy Agency, "The Statute of the IAEA" (1956), Article XII.A, accessed March 8, 2018, https://www.iaea.org/about/statute.

integration brought about by the European Coal and Steel Community from 1952 onwards.[23] The Treaty of Rome that established Euratom in 1957, however, also contained provisions for safeguards on nuclear material within the territories of its Member States. The purpose of Euratom safeguards measures as given in Article 77 of the Treaty of Rome are to verify the non-diversion of materials from their intended purposes, and to ensure observance of "obligations assumed by the Community under an agreement concluded with a third State or an international organisation."[24,25] The Treaty of Rome (Article 81) also gives Euratom the ability to send inspectors into Member States. These inspectors, were to "at all times have access to all places and data and to all persons… to the extent necessary in order to apply such safeguards to ores, source materials and special fissile materials and to ensure compliance with the provisions of Article 77."[26] The initial membership of Euratom was identical to that of the original membership of the European Coal and Steel Community: Belgium, the Federal Republic of Germany (FRG), France, Italy, Luxembourg, and the Netherlands.

In the case of IAEA verification, the development of safeguards approaches for different types of facilities, as well as the actual application of safeguards, was done on a facility-by-facility basis, starting with simpler facilities. The IAEA started off small – its first published safeguards

[23] Mervyn O'Driscoll, "The European Parliament and the Euratom Treaty: Past, Present, and Future," Working Paper ENER 114 EN, Energy and Research Series, Directorate-General for Research (Luxembourg: European Parliament, 2001), 1.
[24] "Treaty establishing the European Atomic Energy Community (Euratom)" (Rome, March 25, 1957), art. 77, http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:11957A/TXT&from=EN.
[25] This provision became highly pertinent during preparations for the entry into force of the NPT, wherein the IAEA and Euratom negotiated at length to delineate responsibilities of each organization under the NPT verification mandate.
[26] "Treaty establishing the European Atomic Energy Community (Euratom)," art. 81.

approach, issued in 1961, only applied to reactors with power less than 100 MW thermal.[27] The IAEA's safeguards system was extended with safeguards approaches for larger reactors (1963),[28] reprocessing plants (1966),[29] and fuel fabrication and conversion plants (1968).[30] No IAEA agreed safeguards approach existed for enrichment plants of any type, however, by the time the NPT entered into force in 1970. At this point, neither the IAEA nor Euratom had any experience implementing safeguards at enrichment facilities.

The absence of pre-NPT enrichment safeguards was brought about by the fact that until the early 1970s, all operating enrichment facilities were located in nuclear weapon states, and all were or had been connected to the nuclear weapons programs of those countries. In the case of the United States, although enrichment activities in Oak Ridge, TN at Y-12 ceased in 1946 (as EMIS was far less energy efficient than gaseous diffusion), operation of K-25 for weapons HEU production continued through 1964, when the United States ceased producing HEU for nuclear weapons, after which the facility switched to LEU production.[31] The United States completed two additional gaseous diffusion facilities during the 1950s: one in Portsmouth, OH that produced HEU for weapons and naval propulsion, and one in Paducah, Kentucky, which produced LEU for further enrichment at the Oak Ridge and Portsmouth plants.[32] In the late 1940s, the Soviet Union built its

[27] "The Agency's Safeguards," INFCIRC/26 (Vienna: International Atomic Energy Agency, 30 March 1961).
[28] "The Agency's Safeguards: Extension of the system to large reactor facilities," INFCIRC/26, Add. 1 (Vienna: International Atomic Energy Agency, 9 April 1964).
[29] "The Agency' Safeguards System (1965, as Provisionally Extended in 1966)," INFCIRC/66/Rev.1 (Vienna: International Atomic Energy Agency, 12 September 1967).
[30] "The Agency' Safeguards System (1965, as Provisionally Extended in 1966 and 1968)," INFCIRC/66/Rev.2, (Vienna: International Atomic Energy Agency, 16 September 1968).
[31] U.S. National Nuclear Security Administration, *Highly Enriched Uranium: Striking a Balance*, Rev. 1 (2001), 58.
[32] Ibid., 27.

own gaseous diffusion enrichment plants, as part of its own nuclear weapons effort.[33] Likewise, the United Kingdom constructed a GDP at Capenhurst in the early 1950s, which produced HEU for the British nuclear weapons program.[34] Following this pattern, France and China built gaseous diffusion enrichment facilities dedicated to their own weapons efforts at Pierrelatte[35] and Lanzhou[36] respectively, during the late 1950s through the mid-1960s. Before the growth of commercial nuclear power industry in the 1970s,[37] these unsafeguarded enrichment facilities were sufficient in capacity for providing material for civil nuclear enterprises around the world. Thus, there was no need for other countries (certainly those without nuclear weapons aspirations) to acquire enrichment facilities of their own, particularly given the vast expense and resources required for constructing and operating a GDP. For the same reasons, notwithstanding nonproliferation reasons, enrichment technology was never transferred from a NWS to a NNWS, and thus the necessity of IAEA safeguards measures for the material involved in such a technology transfer never came into question.

Again, given the findings of the Acheson-Lilienthal and the UNAEC reports, it may have been just as well that safeguards were never undertaken at GDPs during this period. Elaborating on the findings of the 1946 UNAEC report, a 1000 tSWU/a GDP (i.e. a small commercial-scale facility)

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[33] Oleg Bukharin, "Understanding Russia's Uranium Enrichment Complex," *Science and Global Security* 12, no. 3 (2004): 193–218.
[34] UK Ministry of Defence, "Historical Accounting for UK Defence Highly Enriched Uranium" (March 2006), http://fissilematerials.org/library/mod06.pdf.
[35] Commissariat à L'énergie Atomique, "Pierrelatte: Uranium Enrichment Plant," Fact Sheet (2009). http://fissilematerials.org/library/cea10.pdf.
[36] Hui Zhang, *China's Uranium Enrichment Capacity: Rapid Expansion to Meet Commercial Needs*, Belfer Center for Science and International Affairs, (Boston: Harvard University, August 2015), 2.
[37] In 1970, global nuclear generation capacity was 17.3 gigawatts, whereas by 1980, it had grown to 130.9 gigawatts. See U.S. Energy Information Administration, "Global generation capacity for nuclear power has grown to over 346 gigawatts since 1955," *Today in Energy* (May 17, 2012), http://www.eia.gov/todayinenergy/detail.php?id=6310.

with a typical specific process inventory of 0.2 kgU/kgSWU/a[38] would have a process inventory of 200 metric tons of uranium. Large amounts of material would be deposited each year inside the piping, diffusers, and other equipment in such a facility. Estimating the mass of this material (known as 'holdup') with necessary precision to rule out the possibility of diversion of a weapons-usable quantity of nuclear material would have been challenging using contemporary technology and would have likely required inspector access to all areas of the plant, including those deemed sensitive by the operator. Security and information protection practices at these facilities would have been stringent. In the United States, for example, the precedent for information protection came from the absolute secrecy of the Manhattan Project, which metamorphosed into classification policy under the Atomic Energy Act of 1946. This new law prohibited the United States from exchanging any information on industrial uses of nuclear energy with other nations, pending congressional approval of "effective and enforceable international safeguards against the use of atomic energy for destructive purposes."[39] Information controlled under the Act was classified under the designation "Restricted Data," which was defined as "all data concerning the manufacture or utilization of atomic weapons, the production of fissionable material, or the use of fissionable material in the production of power."[40] Thus, under this legislation, any transfers of any information concerning enrichment technology to a foreign entity would have been unlawful. Although these control provisions were loosened under the Atomic Energy Act of 1954, which allowed for the transfer of Restricted Data to foreign countries under cooperation agreements (so-

[38] J. Michael Whitaker, "Uranium Enrichment Plant Characteristics – A Training Manual for the IAEA," ISPO-310/R1 (U.S. Program for Technical Assistance to IAEA Safeguards, 2005), 14.
[39] "Atomic Energy Act of 1946 (Public Law 585, 79th Congress)" (1946), sec. 10(a)(1), excerpted from *Legislative History of the Atomic Energy Act of 1946 (Public Law 585, 79th Congress)* (Washington: U.S. Government Publishing Office, 1965).
[40] Ibid., sec. 10(b)(1).

called '123 Agreements') and with presidential approval,[41] the control of enrichment information remained tight.

Safeguards at centrifuge enrichment facilities, meanwhile, amidst the context of enrichment safeguards writ large, were generally a low priority in the years between World War II up to the late 1960s (relative to in the 1970s and beyond), as centrifuge enrichment technology was still in its infancy at the time. Although it would have been apparent that material balance difficulties would have been easier to overcome at centrifuge facilities, given the vastly lower amount of in-process inventory in a GCEP versus a GDP, policies for information protection were still restrictive. As long as enrichment capacity remained in the hands of nuclear weapon States, designing international safeguards systems for enrichment facilities, from a horizontal proliferation perspective, was not a particularly pressing issue.

Tightening the Jaws: Moving Towards the 1960 Quadripartite Classification Guide

While enrichment facilities were operated solely by nuclear weapon States until the early 1970s, research and development efforts were taking place earlier, nevertheless, in Non-Nuclear Weapon States—in particular, the Netherlands and Germany. Meanwhile, research and development efforts for centrifuge enrichment in the United States, in their earliest years, were fairly modest. This was largely because no need existed at the time for additional U.S. enrichment capacity, which was already satisfied by proven gaseous diffusion technology. From 1954-1960, the sole U.S. effort took place in an experimental group at the University of Virginia. This group nevertheless made

[41] "Atomic Energy Act of 1954," Public Law 703, Chapter 1073 (Washington, DC: U.S. Government Publishing Office, August 30, 1954), sec. 144(a).

some advances, both on spinning supercritical centrifuges through critical frequencies, and on the operation of subcritical centrifuges. The latter took place from 1958 onwards, after the arrival of Gernot Zippe, an Austrian engineer who had participated in Soviet development of a subcritical centrifuge during his time as a Soviet prisoner of war following World War II.[42] By the end of the 1950s, it was apparent to the U.S. Atomic Energy Commission (USAEC) that isotopic separation could be carried out using centrifuges at a cost comparable to gaseous diffusion. A 1959 study by General Electric estimated that the United States could construct a small enrichment plant producing 500 kg of 95%-enriched uranium per year using Soviet-type short-tube centrifuges within a 2-3 year period.[43] The USAEC was also aware, however, that other nations, in particular the Netherlands and the Federal Republic of Germany (FRG, or West Germany), had made more committed efforts to developing centrifuge enrichment technology. By 1960, the USAEC believed that West German centrifuge R&D program was the most advanced in the world, surpassing U.S. efforts.[44]

Given the progress in centrifuge R&D that had taken place in the late 1950s (despite relatively meager U.S. efforts), awareness of proliferation risks associated with the centrifuge grew among American policymakers. A 1960 study conducted by the Union Carbide Nuclear Company found that an Nth country pursuing a weapons program may find the centrifuge route easier than plutonium production in a reactor, given the state of centrifuge technology at the time.[45]

[42] U.S. Atomic Energy Commission, *Gas Centrifuge Method of Isotope Separation*, AEC 610/15 (April 9, 1960), 1, 11, http://digitalarchive.wilsoncenter.org/document/115362.
[43] Ibid., 16–17.
[44] Ibid., 14.
[45] S.A. Levin, D.E. Hatch, and E. Von Halle, "Production of Enriched Uranium for Nuclear Weapons by Nations X, Y, and Z by Means of the Gas Centrifuge Process," KOA-662, Union Carbide Nuclear Company (February 1960), https://digitalarchive.wilsoncenter.org/document/115305.

Clandestine operation of centrifuges, the study found, was a particular danger, given the small footprint and power consumption of a centrifuge facility relative to a GDP of the same capacity. The USAEC, at the time, estimated that eleven countries[46] were capable of exploiting the centrifuge enrichment method.[47] The newfound attractiveness of the gas centrifuge raised a quandary for the United States as to how to prevent newcomer states from acquiring material for nuclear weapons with this technology. Two strategies were proposed: safeguards at facilities based on unclassified exports of centrifuge technology were envisioned (although these measures never materialized, as no exports took place), and tighter information controls on gas centrifuge technology were recommended.[48] Within the borders of the United States, restricting information on centrifuge enrichment was a simple endeavor. The prevailing situation in 1960 was that the U.S. centrifuge R&D effort was formally considered a classified program (with the exception of Zippe's work on reconstructing the Soviet short-tube centrifuges, which concluded in the United States in July 1960), although information produced under the program would be declassified until a breakthrough demonstrating the feasibility of the technique occurred.[49] Now that a breakthrough had taken place, the United States could merely stop declassifying new centrifuge R&D. The Netherlands and the FRG, however, had been conducting centrifuge R&D on an unclassified basis. It was clear to the USAEC that U.S. classification measures would do little to control the flow of technical information on centrifuge design if Netherlands and the FRG continued to publish their work openly.

[46] These countries were the United States, the USSR, the UK, Austria, Belgium, the Federal Republic of Germany, France, Japan, the Netherlands, Sweden, and Switzerland.
[47] U.S. Atomic Energy Commission, *Gas Centrifuge Method of Isotope Separation*, 43.
[48] Ibid., 39-40.
[49] Ibid., 20.

Thus, the United States embarked on a multilateral effort to curtail the availability of centrifuge enrichment information, both within its own borders, and from Europe. On the basis of the recommendations of an April 1960 USAEC report,[50] the United States approached the Netherlands, the FRG and the United Kingdom (the latter of which had recently showed interest in centrifuge development) to cooperate on the classification of centrifuge information.[51] Achieving a common classification standard across all four countries was not a trivial endeavor. The FRG, for example, was concerned that classification of formerly open centrifuge research would heighten other nations' suspicions of its nuclear intentions,[52,53] calling into question its compliance with its commitment to the Western European Union not to manufacture nuclear weapons within its territory.[54] Furthermore, formal classification of nuclear technical information in Euratom Member States could contravene provisions for dissemination of information under the Treaty of Rome. Articles 16-23 of the Treaty require Euratom Member States to ask owners of nuclear-related patent applications to transmit them to the Euratom Commission, and in cases where the patent owner does not consent to this, the Euratom Commission can require the Member State to transmit the patent.[55] Patents in possession of the Euratom Commission, under Article 12 of the Treaty,

[50] Ibid., 40.
[51] For further information on this effort, see William Burr, "The Gas Centrifuge Secret: Origins of a U.S. Policy of Nuclear Denial, 1954-1960," National Security Archive Electronic Briefing Book No. 518, The National Security Archive (Washington: George Washington University, June 29, 2015). http://nsarchive.gwu.edu/nukevault/ebb518-the-gas-centrifuge-secret-origins-of-US-policy-of-nuclear-denial-1954-1960.
[52] U.S. Embassy Bonn, "Ref: Deptel 2537," Bonn 2312, RG 50, Central Decimal Files 1960-1963, 611.62A45/6-760 (June 7, 1960), obtained from http://nsarchive.gwu.edu/nukevault/ebb518-the-gas-centrifuge-secret-origins-of-US-policy-of-nuclear-denial-1954-1960/doc%2013%206-7-60%20germans.pdf.
[53] The 1960 Quadripartite Classification Guide likely elevated already overblown East German fears of a West German nuclear weapons effort. See Alexander Bollfrass, "*The Half-Lives of Others*," (PhD diss., Princeton University, 2017), 96–97.
[54] "Brussels Treaty, as amended by the Protocol modifying and completing the Brussels Treaty, signed at Paris on October 23, 1954," (Western European Union, 1954), part I, art. I.
[55] "Treaty establishing the European Atomic Energy Community (Euratom)," art. 16.

could then be disseminated to persons, enterprises, and governments of Euratom Member States. Security classification of information would pose an obstacle to this process. This problem, however, was ultimately resolved through a 'gentlemen's agreement,' by which the Netherlands and the FRG agreed to informally classify centrifuge enrichment information, so as to avoid political issues with Euratom, while the United States and United Kingdom formally classified their centrifuge research from August 1, 1960 onwards.[56] Classification policy in the four countries was governed by a common guide, often referred to as the 1960 Quadripartite Classification Guide.[57] This guide assigned classification levels to different types of centrifuge information, as shown in Table 3-1. The equivalent level to the U.S. 'Confidential' level was designated as a lower classification level, while the equivalent of the U.S. 'Secret' level was used for classifying more sensitive information. As is evident from Table 3-1, the 1960 Quadripartite Classification Guide was not particularly nuanced. In essence, it called for a blanket classification level of 'Secret' to all information concerning centrifuge or cascade technology. Nevertheless, the need for nuance at this time was not particularly pressing: centrifuge work, at least in the Western world, was still only taking place on a laboratory scale, and the number of personnel authorized to access centrifuge information was rather low. In the United States—even by 1967—only six hundred people had ever been exposed to classified U.S. centrifuge technology information, including those no longer with access, whereas about twenty thousand people had been exposed to classified GDP

[56] U.S. Atomic Energy Commission, *A Study of the Gas Centrifuge as it Relates to the Proliferation of Nuclear Weapons*, excised copy (1967), 55, Department of Energy mandatory declassification review release.
[57] U.S. Atomic Energy Commission, "Gas Centrifuge Classification Guide," RG 59, Central Decimal Files 1960-1963, 103-AEC/10-1960 (1960), obtained from http://nsarchive.gwu.edu/nukevault/ebb518-the-gas-centrifuge-secret-origins-of-US-policy-of-nuclear-denial-1954-1960/doc%2020A%207-27-60%20class%20guide.pdf.

technology.[58] With these numbers in mind, a simple classification guide made sense at the time. As will be discussed later, the 1960 guide was amended in later years, as the technology neared commercialization, which brought on the need for the assignment of explicit (and often lower) classification levels for individual components, in order to allow for the manufacturing of these components on an industrial scale.

Table 3-1: Classification levels assigned to centrifuge information in the 1960 Quadripartite Classification Guide. Source: U.S. Atomic Energy Commission, "Gas Centrifuge Classification Guide" (1960).

Information	Classification Level
1. All information as to the design, construction and operation of cascades of centrifuges for the separation of isotopes.	Secret
2. Plant and pilot plant design (both technical and economic features).	Secret
3. Information on design, construction and operation of centrifuges operating at peripheral speeds >400 m/sec or on new or improved units regardless of peripheral speed.	Secret
4. Hydrodynamics of gas flow in centrifuges or cascades 4.1 Separating efficiencies	Secret Secret
5. Designs of bearings for gas centrifuge units other than those designs already in the public domain.	Secret
6. Existence of major new steps 6.1 Fact of continuing or newly imposed classification of centrifuge work 6.2 Level of effort on centrifuge program 6.3 Other information on new steps	 Unclassified Confidential Secret

Tiptoeing Around the Genesis of Gas Centrifuge Enrichment Safeguards

Following the breakthroughs of the late 1950s and implementation of the 1960 classification guide, centrifuge research accelerated in the United States, with the USAEC's annual investment growing from between $60,000 and $300,000 pre-1960, to an average of $2.3 million per year from 1960

[58] U.S. Atomic Energy Commission, *A Study of the Gas Centrifuge as it Relates to the Proliferation of Nuclear Weapons*, 53.

through 1966.[59] In the Netherlands, centrifuge R&D work was given formal oversight by a Supervisory Committee in 1962, after which several advances were made in centrifuge design, including the use of maraging steel rotors.[60] Research in the FRG continued at a steady pace as well – although the separative performance of German-designed centrifuges did not improve measurably from 1960-1968, in the latter part of the decade, significant progress was made. Between 1968 and 1973, an 8-fold increase to the separative performance of centrifuges was achieved by the FRG.[61] Centrifuge research in the UK continued as well, although the UK faced a decision on whether to enrich fuel for its civil reactors using proven gaseous diffusion technology that it had already developed, or to take a riskier path with centrifuge enrichment—a choice that the Dutch and Germans did not have to make. Nevertheless, a March 1967 review on progress in centrifuge technology indicated that centrifuges would be the favorable option.[62] By the late 1960s, the commercial operation of GCEPs for enriching fuel for civil power reactors seemed within grasp. At the same time, efforts began towards collaborative development and commercialization of centrifuges between the three European countries. All three nations had reasons to collaborate in this area: both the Netherlands and the FRG were ready to test their technology at a pilot plant scale. Building a joint facility outside the FRG would provide political assurances that the FRG's centrifuge efforts were entirely peaceful in nature. Meanwhile, the UK Government was eager to demonstrate its willingness to collaborate with Europe, in support of reapplication bid for the European Economic Community, following its second rejected application in 1967.[63] Following

[59] Ibid., 14.
[60] R.B. Kehoe, *The Enriching Troika: A History of Urenco to the Year 2000* (Marlow, UK: Urenco Limited, 2002), 24-25.
[61] H.J. Dibbert and U. Brate, "Überlegungen zum Anreicherungsmarkt und zur Errichtung europäischer Zentrifugenanreicherungsanlagen," Uranit report, BArch, B 136/6119, Microfiche 3 (Jülich, 16 March 1973).
[62] Kehoe, *The Enriching Troika*, 32.
[63] Kehoe, *The Enriching Troika*, 31–32.

approximately 18 months of formal negotiations concluding in November 1969,[64] agreement was reached and formalized at the signing of the Treaty of Almelo on March 4, 1970.

Through the Treaty of Almelo,[65] the three governments, known as the "Troika," undertook to "promote the establishment and operation of joint industrial enterprises to build plants for the enrichment of uranium by the gas centrifuge process and to operate such plants and otherwise exploit that process on a commercial basis."[66] The Treaty established a Joint Committee (JC) made up of representatives of each of the Troika governments, which would oversee the enterprise. Activities under the agreement would be carried out by two companies: an enrichment organization responsible for owning and operating plants, which would soon be christened Urenco, and a company for conducting R&D, centrifuge manufacturing and plant construction, which was named Centec. Each of these two companies was to be equally owned in three parts by Dutch, British, and German shareholder companies. Urenco shares were held by Ultracentrifuge Nederland (UCN), the UK Atomic Energy Authority (UKAEA), and by Uran-Isotopentrennungs-Gesellschaft mbH (Uranium Isotope Separation Corporation, Uranit), while Centec shares were controlled by UCN, the UKAEA, and the Gesellschaft für nukleare Verfahrenstechnik (Corporation for Nuclear Process Technology, GnV), a corporation formed from four German companies that had presently been involved with centrifuge work.[67] Under the auspices of this new

[64] A history of these negotiations is given in Susanna Schrafstetter and Stephen Twigge, "Spinning into Europe: Britain, West Germany and the Netherlands: Uranium Enrichment and the Development of the Gas Centrifuge, 1964-1970," *Contemporary European History* 11, no. 2 (2002): 253–272.
[65] "Agreement between the United Kingdom of Great Britain and Northern Ireland the Federal Republic of Germany and the Kingdom of the Netherlands on Collaboration in the Development and Exploitation of the Gas Centrifuge Process for producing Enriched Uranium, Almelo, 4 March 1970," Treaty Series No. 69 (London: HM Stationery Office, 1971).
[66] Ibid., art. I(2).
[67] Kehoe, *The Enriching Troika*, 37.

agreement, each country was to build a pilot plant for demonstrating its centrifuge technology. The UK was to build a 25 tSWU/a pilot facility at its existing nuclear site at Capenhurst, while the Netherlands and the FRG would build each of their 25 tSWU/a facilities at a new location in Almelo, the Netherlands. The Treaty also established another set of rules for the handling of classified information, including the continuation of common classification policy,[68] and a rule prohibiting the "admission of visitors to restricted areas of premises… unless they are authorised to have access to classified matter of the corresponding security grading in their own State."[69]

Provisions for safeguards were also written into the Treaty of Almelo. By the time the agreement was being drafted, it was clear that any Troika enrichment facilities based in the Netherlands or in Germany would obviously be subject to Euratom safeguards, as well as IAEA safeguards under the auspices of the NPT (in collaboration with Euratom), following the ratification of treaty by the two countries. Furthermore, the Treaty of Almelo, Article X, affirmed that nothing in the Treaty altered the obligations of the Troika under the Euratom Treaty. Ostensibly, this would mean that any classification rules established under the Treaty of Almelo, such as limits to the access of uncleared visitors, would be trumped by provisions of the Euratom Treaty, such as the Article 81 provisions for unlimited inspector access in fulfillment of the Article 77 goals of Euratom safeguards. Meanwhile, the NPT had been signed in July 1968, the agreement had yet to enter into force, and the model safeguards agreement pursuant to Article III of the Treaty had not yet been negotiated. Nevertheless, with the possibility of future NPT safeguards in mind, Article VII(2)(b) bound parties of the Treaty to apply any procedures resulting from agreements concluded with the IAEA. Thus, Euratom safeguards would apply at Almelo, as well as IAEA comprehensive

[68] "Agreement between the United Kingdom of Great Britain and Northern Ireland…," Annex II, para. 5(b).
[69] Ibid., Annex II, para. 8(a).

safeguards, pending an agreement between IAEA and Euratom on implementation of these safeguards,[70] and Dutch NPT ratification. Under the Treaty, the Joint Committee as tasked to "consider and decide upon any questions concerning the safeguards provided for in Article VII."[71] This latter provision, which essentially requires safeguards policy to be made with the consensus of the three States, would challenge the Troika in later years.

With the founding of the Troika, the impending construction of a GCEP in a non-nuclear weapon state finally drew some serious attention to the issue of centrifuge safeguards. Pressure came first from the Soviet Union, starting in 1967, during which it made a proposal to extend the IAEA's safeguards system once more (as had been done with other fuel cycle facilities) to cover enrichment plants.[72] It is possible that the Soviets' concern could have been borne out of its success, relative to the rest of the world, with developing centrifuge technology. Unbeknownst to the Western world,[73] the USSR had completed its first pilot GCEP in 1957,[74] far before any other nation achieved the same. The Soviets may have been more acutely aware of the proliferation consequences of GCEP operation than other States, given that they had long proven the technology by the time the Europeans were ready to construct a pilot plant. As Troika negotiations loomed

[70] As mentioned earlier in this chapter, Article 77(b) of the Euratom treaty obliges the Euratom Commission to "satisfy itself" of compliance with agreements with third countries or international organizations within the territories of its Member States. Via this language, Euratom would have a legal stake in NPT verification within all Euratom NNWS, including the Netherlands, even though Article III of the NPT explicitly calls for IAEA safeguards verification.
[71] Ibid., art. II(5)b.
[72] Allan McKnight, *Atomic Safeguards: A Study in International Verification* (New York: United Nations Institute for Training and Research, 1971), 58.
[73] Even by 1970, U.S. intelligence assessments concluded that the Soviet Union had not constructed GCEPs. See R. Scott Kemp, "The Nonproliferation Emperor Has No Clothes," *International Security* 38, no. 4 (2014): 50; U.S. Central Intelligence Agency, "A Modest Suggestion for a Review of the Bidding," *Studies in Intelligence* 14, no. 2 (1970): 128–132, https://www.cia.gov/library/readingroom/docs/CIA-RDP78T03194A000300010010-1.pdf.
[74] Oleg Bukharin, *Russia's Gaseous Centrifuge Technology and Uranium Enrichment Complex*, Program on Science and Global Security, Princeton University (Princeton, NJ, 2004): 10–11.

on the horizon, calls to develop an IAEA GCEP safeguards approach became more urgent. Enrichment safeguards were discussed at the June 1968 IAEA Board of Governors (BoG) meeting, during which a decision was made for the Director General of the IAEA, Sigvard Eklund, to convene a panel of experts to advise him at a timely juncture, based on his consultations.[75]

In March 1969, the Soviet Union initiated discussions with the United States towards convening a panel for drafting a safeguards approach for enrichment facilities, with specific reference to GCEPs, and argued that the issue should be brought up in the BoG meeting that June.[76] The U.S. Mission saw merit in the Soviet proposal, given that negotiations among the Troika were ongoing, while also noting that some time would be required for considering technical issues.[77] The U.S. State Department, however, recommended against any consideration of enrichment safeguards at the June BoG meeting, which it assessed to be "premature and unwise."[78] The State Department did not see an urgent need for developing a safeguards approach, since a European GCEP was not expected to be in operation for at least another two years. The USAEC was also undertaking studies on safeguards implementation at enrichment facilities, which would not yet be complete by the June 1969 Board meeting.[79] Third, the State Department feared that opening up discussions on enrichment safeguards could hurt U.S. efforts to promote the NPT,[80] essentially scaring away key NNWSs (particularly the FRG) from ratifying the agreement. Thus, the United States resolved to keep a discussion on enrichment safeguards from reaching the BoG, even to the extent that it

[75] U.S. Department of State, State 51601, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 7, AE 13: Uranium Enrichment, 1969 (April 4, 1969), 2.
[76] U.S. Embassy Vienna, IAEA Vienna 1093, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 7, AE 13: Uranium Enrichment, 1969 (March 6, 1969).
[77] Ibid., 2.
[78] U.S. Department of State to Embassy Vienna, State 51601 (April 4, 1969), 1.
[79] Ibid., 2.
[80] Ibid., 2.

instructed the U.S. Mission to the IAEA to resist any Soviet pressure to discuss provision of design information for the new GCEP planned in the Netherlands. If the USSR were to raise this as an issue, the U.S. Mission was instructed to argue that safeguards procedures for the facility would not be implemented until conclusion of an IAEA-Euratom safeguards agreement,[81] thus removing any urgency from any effort to work towards a safeguards approach for Almelo.[82] Nevertheless, the State Department did prompt U.S. Mission staff to inquire about Soviet technical studies on the issue. Upon being informed of the U.S. position, Soviet mission staff indicated that they would not bring up the matter any further.[83]

Although the United States was outwardly reluctant to discuss GCEP safeguards, behind closed doors, nascent U.S. efforts were taking place to examine GCEP safeguards. In July 1968, a brief report on enrichment safeguards (both at GDPs and GCEPs) was produced by Union Carbide, which operated the K-25 plant in Oak Ridge.[84] The section of the report dedicated to GCEPs ran only six pages long. Nevertheless, the report tackled what would become the main issue in question regarding GCEP safeguards: the degree of inspector access to a facility necessary for adequate safeguards verification. Two access levels were considered: one in which inspectors would only be able to measure material flows and electrical power intake at a plant's perimeter, and the other allowing inspectors unlimited access to the plant for the purpose of conducting a full material balance (but not to extraneous sensitive information, such as the rotational speed of the

[81] Ibid., 3.
[82] Two years later, a dispute over whether to produce a safeguards approach for Almelo caused a delay in signature of the IAEA-Euratom safeguards agreement, in an ironic twist of fate.
[83] U.S. Embassy Vienna, IAEA Vienna 2372, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 7, AE 13: Uranium Enrichment, 1969 (May 7, 1969).
[84] J.F. Hudson and W.D. McCluen, *Safeguards Inspection for Centrifuge and Gaseous Diffusion Plants*, Report Number K-P-3559, Union Carbide Corporation, TNA FCO 55/760 (July 24, 1968).

centrifuges).[85] Physical security measures would also be implemented by the inspectorate, for the purpose of deterring material diversions.[86] Remarkably, in spite of the stringent classification policies that were in place at the time, the report's authors assumed that if inspectors were to access a GCEP to verify material balance, the only "meaningful access" would be "complete access to all information and data necessary,"[87] given the relative ease with which product enrichments could be changed at a plant. This observation foreshadowed an internal debate within the U.S. Government (and even within divisions of the USAEC) that would continue over the next few years, on the relative importance of safeguards effectiveness and information protection. These discussions also partly explain the sensitivity with which the United States treated GCEP safeguards externally at the time. In these early days, the U.S. Government was not yet ready to take a public stance on GCEP safeguards measures with other technology holders or inspectorates.

The United States continued to be highly sensitive to international discussions on enrichment safeguards. Internally, the U.S. State Department was concerned that any debate over enrichment safeguards measures could be used by the Eastern bloc to stoke fears that the FRG was secretly working on a nuclear weapons program. One incident, provoked by an address by UN Secretary General U Thant to the Conference of the Committee on Disarmament (CCD) in 1970, is particularly telling in this regard. In this speech, Thant reportedly suggested that the CCD study proliferation issues related to the gas centrifuge, and that the technology could pose a problem regarding the NPT.[88] This alarmed the United States, which surmised that a Soviet national within

[85] Ibid., 5–10.
[86] Ibid., 6. Note that the IAEA does not (nor has the legal right to) implement any physical security measures itself under comprehensive safeguards implemented pursuant to the NPT.
[87] Ibid., 5.
[88] U.S. Embassy Bonn, Bonn 2707, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 17, SCI 10: FRG/UK/Dutch Centrifuge Cooperation, 1970, (March 11, 1970).

the UN Secretariat in New York encouraged the Secretary General to include this statement, in order to support Soviet efforts to embarrass the FRG in light of its recent progress towards building a centrifuge pilot plant.[89] CCD delegates from the FRG, the UK, and Canada fueled speculation on this issue.[90] Bringing up the issue of gas centrifuge enrichment in the CCD, in U.S. eyes, could cloud or conflict with IAEA's work on NPT safeguards in Vienna. Upon approaching the author of Thant's speech, however, the State Department learned that the speechwriter, William Epstein, considered centrifuge enrichment as an important proliferation issue, based upon his consultations with scientists in New York. Epstein was convinced that clandestine centrifuge enrichment facilities could be hidden at different locations with a country, and that safeguards alone might not be sufficient for mitigating the proliferation risk posed by the technology.[91] Although the State Department ultimately concluded that Thant's comment was based on Epstein's opinion,[92] and was not influenced by Soviet machinations, U.S. fears persisted about the Soviets using safeguards as a propaganda tool against the FRG's centrifuge program. On February 24, 1970, less than a week after the United States inquired with Epstein about U Thant's CCD speech, Poland raised the centrifuge safeguards issue again during a plenary session of the CCD. In the context of IAEA efforts to provide fissionable material to its Member States, the Polish delegate declared that the "relative haste in implementation" of the Troika's centrifuge work was not understandable, and stating that lack of controls on the centrifuge process would "threaten international security and defeat non proliferation effort."[93] Less than two weeks after this event, on March 6, 1970, the

[89] U.S. Mission Geneva, Geneva 546, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 17, SCI 10: FRG/UK/Dutch Centrifuge Cooperation, 1970 (February 19, 1970).
[90] Ibid., 1.
[91] Ibid.
[92] Ibid., 2.
[93] U.S. Mission Geneva, Geneva 582, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 17, SCI 10: FRG/UK/Dutch Centrifuge Cooperation, 1970 (February 24, 1970), 1–2.

Soviet Ambassador to the Netherlands, Ambassador Lavrov, criticized the Troika's centrifuge effort during a reception celebrating Ghana's National Day. A U.S. cable reports that Lavrov articulated Soviet concern over "inadequate controls" in the Treaty of Almelo (signed only two days prior), "which had NPT implications and could easily permit Germans to manufacture atomic weapons," while also commenting on the inadequacy of Euratom safeguards measures.[94] Lavrov also indicated that he had delivered similar comments to the British ambassador to the Netherlands. U.S. embassy staff in The Hague sniffed trouble, linking the Polish CCD comments with the Soviet ambassador's recent remarks, informing Washington of its conviction that the USSR was coordinating its Warsaw Pact allies to raise opposition to centrifuge development by the Troika.[95]

The veracity of these fears was debated over the coming days. On March 11, the U.S. Mission in Geneva reported, soon after dispatch of Ambassador Lavrov's comments, that other Warsaw Pact states, including Bulgaria, Romania, Czechoslovakia and Hungary, had not raised the issue of centrifuge safeguards at the CCD during its recent plenary session,[96] and that this evidence did not support the idea of a coordinated Warsaw Pact effort. The U.S. Embassy in Bonn, however, shared the concern of U.S. diplomats in The Hague. A cable from Bonn noted that centrifuge development in the FRG was a delicate domestic political issue, and that "needling" by the Soviets would make the debate a more pertinent issue, which could even affect the FRG's position on NPT ratification.[97] The message emphasized a need to rebut any Soviet messaging that insinuated that the West

[94] U.S. Embassy The Hague, The Hague 787, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 17, SCI 10: FRG/UK/Dutch Centrifuge Cooperation, 1970 (March 10, 1970), 1.
[95] Ibid., 2.
[96] U.S. Mission Geneva, Geneva 786, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 17, SCI 10: FRG/UK/Dutch Centrifuge Cooperation, 1970 (March 11, 1970).
[97] U.S. Embassy Bonn, Bonn 2707, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 17, SCI 10: FRG/UK/Dutch Centrifuge Cooperation, 1970, (March 11, 1970), 1.

German centrifuge program was evidence of "bad faith" under the NPT.[98] The State Department sought to meld the positions of The Hague, Bonn, and Geneva by preparing talking points on centrifuge safeguards, to be used if the Soviets continued to comment on the Treaty of Almelo, or on the efficacy of Euratom safeguards. If this were to happen, the U.S. would argue that construction of enrichment facilities was permitted under the NPT, that the Treaty of Almelo explicitly indicated the Troika States' intention to uphold their nonproliferation obligations, and that the United States had confidence in Euratom safeguards as well as the ability of the IAEA and Euratom to reach a safeguards agreement.[99] U.S. concerns over Soviet interference subsided, however, as the Dutch government reported that it had not received any communications from the USSR on centrifuge safeguards, noting that the Troika's decision not to construct a GCEP in Germany should make the Soviet concerns "pointless."[100] Neither had the Soviets raised the issue with the UK Foreign and Commonwealth Office (UKFCO).[101] Meanwhile, the FRG Commissioner for Disarmament and Arms Control, Hellmuth Roth, indicated that from the West German perspective, the recent Soviet rhetoric was nothing unusual.[102] Thereafter, threats of an East-West political showdown on GCEP safeguards measures subsided, to the relief of the United States, despite some bluster from Warsaw Pact countries. Nevertheless, these early incidents likely played a role in initial U.S. advocacy for strong safeguards verification measures at GCEPs, as will be discussed in Chapter 4.

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[98] Ibid., 2.
[99] U.S. Department of State, State 36189, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 17, SCI 10: FRG/UK/Dutch Centrifuge Cooperation, 1970 (March 12, 1970).
[100] U.S. Embassy The Hague, The Hague 836, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 17, SCI 10: FRG/UK/Dutch Centrifuge Cooperation, 1970 (March 12, 1970).
[101] U.S. Embassy London, London 1960, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 17, SCI 10: FRG/UK/Dutch Centrifuge Cooperation, 1970 (March 12, 1970).
[102] U.S. Department of State, State 36894, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 17, SCI 10: FRG/UK/Dutch Centrifuge Cooperation, 1970 (March 13, 1970).

The United States was not alone in taking a delicate position on the issue of enrichment safeguards. The United Kingdom also made efforts to prevent the issue from becoming a political issue in international organizations outside the IAEA. At the 25th UN General Assembly (UNGA) in December 1970, a resolution was agreed that requested the IAEA to "pay attention to the safeguards required with respect to new techniques for uranium enrichment" (clearly with reference to centrifuge technology), and to inform the UNGA of its work on the issue at the 26th session.[103] This resolution had been sponsored by Malta.[104] The IAEA, however, was not particularly well equipped at the time to address centrifuge safeguards, given that little in-house knowledge on centrifuge technology was available and that technology holders had not yet engaged with the IAEA on the issue. Nearly one year later, in the UNGA First Committee, Malta declared that the IAEA's report on uranium enrichment was inadequate and that it would present a draft resolution to put further pressure on the IAEA to address new enrichment techniques.[105] Malta, along with other States leaning in favor of the draft resolution argued that the IAEA report served as an "insult" to the UNGA.[106] This step alarmed the UK delegation, which feared that an open debate on GCEP safeguards could allow States to air arguments calling for the application overly onerous safeguards measures at enrichment plants developed under the Troika.[107] Furthermore, as evinced by UK correspondence, the UK was deeply concerned that the draft resolution prejudged the outcome of Euratom-IAEA negotiations on safeguards activities in

[103] "General and Complete Disarmament," A/RES/2661B(XXV), (New York: United Nations General Assembly, December 7, 1970), http://www.un.org/en/ga/search/view_doc.asp?symbol=A/RES/2661(XXV).
[104] UKDis Geneva in New York to FCO, Telegram No. 168, TNA FCO 55/761/75 (November 22, 1971).
[105] Ibid.
[106] UKDis Geneva in New York to FCO, Telegram No. 186, TNA FCO 55/761/83 (November 26, 1971).
[107] UK FCO, "New Techniques of Uranium Enrichment – Background Note," TNA FCO 55/761/80 (November 26, 1971), 1.

Euratom States.[108] In response, the UK attempted to convince Malta to drop the resolution, arguing that the IAEA was giving attention to the matter.[109] While the UK was unable to convince the Maltese not to table the resolution, the UK was able to propose an alternative text to Malta,[110] which was accepted by the Maltese delegation with minor amendments.[111] This text neither criticized the content of the IAEA report, nor did it contain any statements that could prejudice Euratom or IAEA roles in safeguards verification in applicable States. But even though the new Maltese resolution was essentially drafted by the UK, the British delegation did not acknowledge this fact to other delegations, and it was presented in the name of Malta.[112] Ultimately, the British delegation was instructed by the UK Foreign and Commonwealth Office (UKFCO) to vote "without enthusiasm" for the resolution.[113]

False Starts in Technical Cooperation

While centrifuge technology holders took great care in ensuring that international discourse on centrifuge enrichment safeguards did not take any unfavorable turns, by the early 1970s, some international engagement began to take place. The first attempt to discuss the matter took place along the Anglo-American axis. These talks were initiated by General Delmar L. Crowson, Director of the USAEC Office of Safeguards and Materials Management, who reached out to the UK Ministry of Defence in early 1971.[114] The United States intended for these talks to address

[108] Ibid., 2.
[109] Ibid.
[110] UK FCO to UKDis Geneva in New York, Telegram No. 64, TNA FCO 55/761/86 (November 26, 1971).
[111] UKDis Geneva in New York to FCO, Telegram No. 191, TNA FCO 55/761/89 (November 29, 1971).
[112] Ibid., 1.
[113] UK FCO to UKDis Geneva in New York, Telegram No. 79, TNA FCO 55/761/93 (December 3, 1971).
[114] UK Cabinet Office, "Extract from Minutes of NPO(G) Meeting 18/2/71," TNA FCO 55/760/6 (February 23, 1971).

both GDP and GCEP safeguards on a technical basis, and while the discussions would be unclassified, they would not be disclosed to the public.[115] The 1968 Union Carbide report, now three years old, was transmitted along with the request. The UK Cabinet Office reacted tepidly to the request, noting that these talks "could create embarrassment for us,"[116] because neither the UK nor the Troika had taken a position on what an acceptable GCEP safeguards strategy might look like. On top of this, the provision in the Treaty of Almelo (Article II(5)(b)) requiring the Joint Committee to consider safeguards questions meant that the UK would have to first consult the Dutch and West Germans before engaging in GCEP safeguards talks with the United States. However, some British officials recognized a need to at least stay aware of U.S. thinking on enrichment safeguards issues, for the sake of being aware of any American safeguards ideas that ran contrary to UK and Troika interests.[117] Thus, the UK government resolved to respond affirmatively to Crowson's approach, but to treat the diffusion and centrifuge issues separately. Bilateral discussions on diffusion safeguards would be held first, as the UK would need to confer with the Netherlands and the FRG before quadripartite safeguards talks with the United States could take place (as required by the Treaty of Almelo).[118] Frank Panton, of the UK Ministry of Defence, met with Crowson in early May 1971, communicating the UK's desire to separate diffusion and centrifuge talks.[119] In the course of this conversation, it was apparent that Crowson was not aware that the Troika would need to agree on safeguards provisions.[120] In July 1971, the UK informed the USAEC of its reluctance to discuss centrifuge safeguards, on account of its

[115] Ibid.
[116] Ibid.
[117] L.J. Middleton to M.J. Newington, "Safeguarding of Uranium Enrichment Plants," TNA FCO 55/760/10 (April 7, 1971).
[118] R. Press to Newley, "Safeguarding of Uranium Enrichment Plants," TNA FCO 55/760/17 (April 26, 1971).
[119] F.H. Panton to R. Press, "Uranium Enrichment: Safeguards," TNA FCO 55/760/18 (May 5, 1971).
[120] Ibid.

tripartite obligations.[121,122] Although Crowson was displeased by the UK's decision not to engage with the United States,[123] this move bought the UK (and the Troika) more time to keep its options open and develop an approach for GCEP safeguards – the first quadripartite discussions on GCEP safeguards would not take place until April 1972.

In order to defend the flexibility of the to-be-determined Troika GCEP safeguards position, the UK worked in the coming months to ensure that its partners did not commit the group to any undesirable measures or approaches. These efforts caused some strife between the UK and the United States. In July 1971, following a technical meeting in Vienna, a group of U.S. national laboratory personnel learned from their German counterparts that work on GCEP safeguards was underway at Karlsruhe. As a follow-up, a technical-level U.S.-FRG meeting on GCEP safeguards in Karlsruhe was proposed. As the UK had recently objected to meeting with the US about the same issue, Donovan Zook, of the U.S. State Department, informed the UK Embassy in Washington of the possible U.S.-FRG meeting.[124] Two days after receiving this news from Washington, the UKFCO instructed the UK Embassy in Bonn to inform the FRG Foreign Office (Auswärtiges Amt) and the FRG Ministry of Education and Science (BMBW) of the Karlsruhe meeting, and to "suggest that bilateral meetings along the lines envisaged would not necessarily be in the Tripartite interests at this stage," while the Troika position was still in the works.[125] In the same message, the UKFCO warned that "U S experts are likely to be looking for ammunition to

[121] M.J. Newington to L.J. Middleton, "Safeguarding of Uranium Enrichment Plants," TNA FCO 55/760/42 (June 25, 1971).
[122] D.B. Janisch, "Note for the Record" (July 9, 1971), 1, attached to L.J. Middleton to M.J. Newington, TNA FCO 55/760/54 (July 27, 1971).
[123] Ibid.
[124] UK Embassy Washington to FCO, Telegram No. 2455, TNA FCO 55/760/45 (July 19, 1971).
[125] UK FCO to Embassy Bonn, Telegram No. 570, TNA FCO 55/760/47 (July 21, 1971).

support the argument (which we for our part do not accept) that the level of inspection effort allowed under the IAEA model safeguards agreement may not be adequate for centrifuge enrichment plants."[126] Another two days later, on July 23, the UK Embassy in Bonn took action on these instructions, informing the both FRG ministries, neither of which was aware that such a meeting was going to take place.[127] Upon receiving notice on July 26 that a bilateral meeting was indeed about to go ahead, the UK Embassy in Bonn again informed the FRG government, which then engaged with Karlsruhe on the matter.[128] Although it is uncertain exactly what was conveyed to Karlsruhe, the FRG informed the UKFCO that the bilateral meeting would not cover centrifuge safeguards (whether the West German government actually ordered Karlsruhe to steer clear of the issue is unclear). The outcome of this sequence of events, however, is that an American team, upon arrival in Karlsruhe a few days later, was dismayed to find that the GCEP safeguards meeting they had expected was not to be.[129] Key German personnel did not attend the meeting, and unclassified papers to be discussed at the meeting suddenly became classified. Furthermore, the Americans at the meeting inferred that the UK government had deliberately sought to sabotage the meeting. This incident provoked fury from the U.S. State Department, in particular Donovan Zook, who communicated the U.S. Government's frustration with some emotion to a British representative at the UK Embassy in Washington.[130] Nevertheless, while the UKFCO regretted that the United States was offended by what had transpired, the UKFCO assessed that it was "reasonable" to notify the FRG Foreign Office and BMBW about the meeting (even though it seems that the UK did

[126] Ibid.
[127] M.J. Newington to T.A.K. Elliott, "Safeguarding of Uranium Enrichment Plants," TNA FCO 55/760/62 (August 12, 1971), 1.
[128] Ibid.
[129] T.A.K. Elliott to R. Arculus, "Safeguarding of Uranium Enrichment Plants," TNA FCO 55/760/59 (August 9, 1971), 1.
[130] Ibid.

more than merely giving notice).[131] The UKFCO was also offended that the United States had sought to have discussions on GCEP safeguards with the FRG under the banner of them being "purely technical," when the same topic was inherently politically sensitive.[132] The UK FCO, however, quickly worked to defuse the situation. Following a conversation between Donovan Zook and Lawrence Middleton (of the UK Washington Embassy) on August 19, in which both sides acknowledged that they had misunderstood each other's intentions, the Karlsruhe incident appeared to have been resolved.[133] Through this incident, however, the UK Government learned that the U.S. Government was far more sensitive to GCEP safeguards issues than previously thought. Middleton, in closing a letter detailing his conversation with Zook, implored the UK government to be more careful in dealing with the United States on GCEP safeguards in the future.[134]

Setting the Stage for Multilateral GCEP Safeguards Talks

While the United States and Troika were making efforts, largely behind closed doors, to design GCEP safeguards approaches, the IAEA also began exploring the issue. Because the IAEA did not possess substantial knowledge in-house on gas centrifuge enrichment technology, however, the IAEA sought external help from centrifuge experts in putting together its preferred approach. By June 1971, when the UK Government first heard of the IAEA's efforts, the IAEA had already reached out to Gernot Zippe for assistance in drafting a paper on GCEP safeguards.[135] Upon

[131] Newington to T.A.K. Elliott, "Safeguarding of Uranium Enrichment Plants," August 12, 1971.
[132] Ibid., 2–3.
[133] L.J. Middleton to M.J. Newington, "Safeguarding of Uranium Enrichment Plants," TNA FCO 55/760/68 (August 19, 1971), 2.
[134] Ibid., 2.
[135] UK Embassy Vienna to FCO, Telegram No. 233, TNA FCO 55/760/34 (June 11, 1971).

learning of the IAEA's work, the British encouraged the IAEA to proceed slowly as the matter was not particularly urgent (the IAEA Board of Governors had not yet approved INFCIRC/153, and the Netherlands had yet to ratify the NPT),[136] but likely also for the sake of buying time to develop a position with its partners. The United States advised the IAEA to do the same,[137] and a Technical Working Group meeting on safeguards procedures for enrichment facilities to be held in 1971 was postponed, upon request of both the UK and the United States.[138] By late 1971, this meeting had been rescheduled for June 12-16, 1972.[139] This meeting, although delayed, would nevertheless provide an impetus for States to engage on the issue for the first time.

The next chapter will discuss how key States arrived at their initial positions on GCEP safeguards. To close this chapter, however, it is worth summarizing the conditions that governed the centrifuge safeguards debate in the early 1970s. First, stringent information protection measures were imposed on the technology in both the United States and within the Troika, creating a legal dilemma for inspector access to parts of facilities containing classified information and equipment, as well as a challenge for the effective implementation of safeguards. Second, technology holders were under intense political pressure from other States to address GCEP safeguards in an effective manner. However, because the need for enrichment safeguards was a newfound issue (due to the very recent decision to build a GCEP in an NPT non-nuclear weapon State), technology holders had little time to discuss and harmonize their positions, even among close allies, and as is apparent in interactions between the United States, UK, and FRG, technology holders were also highly

[136] Ibid.
[137] Ibid.
[138] UK Embassy Vienna to P.J. Kelly, "Expert Working Group on Safeguarding of Uranium Enrichment Facilities," TNA FCO 55/962/18, January 28, 1972.
[139] U.S. Mission to the IAEA, "Schedule for Agency Safeguards Technical Meetings," Airgram A-868, RG 59, *Subject-Numeric Files, 1970-1973*, Box 2851, AE 3: IAEA 11/24/71 (December 2, 1971), 1.

sensitive with regard to each other's positions. As will be discussed in the following chapter, it was unfortunate that the platforms of the technology holders were so different. As a result, initial international technical-level engagement on GCEP safeguards in the early- to mid-1970s made little headway, with political questions on the applicability and interpretation of INFCIRC/153 instead dominating the discussion.

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Chapter 4 – The Initial Impasse, 1971–1975

As multilateral discussions began in the early 1970s over how to approach IAEA and Euratom GCEP safeguards, disagreements abounded among technology holders over what measures were necessary for effective safeguards, as well as over the interpretation of the legal frameworks that existed for safeguards verification. The IAEA, ill-equipped with the technical means for designing a GCEP safeguards approach itself, reached out to Member States for guidance, which ultimately provided technology holders with the opportunity to delay efforts to agree on a safeguards strategy. Meanwhile Euratom, while equally ill-equipped with technical knowledge, pursued a case against the Netherlands (as well as the UK and the FRG) in pursuit of its right to access cascade halls at the Almelo pilot GCEP, which the Troika ardently sought to prevent. These conditions did not bode well for the efficient negotiation of IAEA and Euratom safeguards activities for Almelo. On one occasion, in which the Troika-Euratom dispute over cascade access resulted in the delay in signature of the IAEA-Euratom safeguards agreement by four months, the growing quagmire of GCEP safeguards jeopardized the implementation of safeguards, writ large, in all six Euratom Member States at the time. While political conditions were unsuitable for agreement on GCEP safeguards in the early to mid-1970s, efforts to mitigate this situation were almost entirely unproductive. Technical cooperation between the United States and the Troika was dysfunctional, producing essentially no useful results that could have been used for resolving any discord on a technical basis. Meanwhile, the IAEA's initial commitment not to pursue cascade hall access directly conflicted with Euratom's decision to visit cascade halls as a part of routine safeguards implementation, thus leading to two contradictory precedents when it came time for a Facility Attachment (FA) to be drafted for Almelo under the IAEA-Euratom safeguards agreement, setting

up a political dilemma that would need to be resolved later in the decade. How did the technology holders and inspectorates get themselves into this mess? This chapter gives an account of the causes, courses and results of these disputes, which further diminished prospects for a technical basis for GCEP misuse verification, driving stakeholders towards a primarily political solution.

Further Context for Early 1970s GCEP Safeguards Discussions

The signing of the Treaty of Almelo in March 1970 came at a transition point in the history of safeguards. Although the Euratom safeguards system had been in place for over a decade at the time the Treaty of Almelo was concluded, the nature of comprehensive IAEA safeguards measures, as called for by the NPT (signed two years prior in 1968), was still to be decided. While an NPT safeguards agreement had not yet been agreed, a further source of uncertainty for safeguards at Almelo came in the form of the future negotiation of an IAEA-Euratom safeguards agreement, which would delineate responsibility and activities for NPT safeguards verification for the two inspectorates. Both of these issues – the application (and applicability) of new NPT safeguards provisions, and the nature and division of responsibility of IAEA and Euratom activities under an IAEA-Euratom agreement, would become sources of contention in the debate over GCEP safeguards.

The conclusion of a text for the model comprehensive safeguards agreement pursuant to the NPT followed shortly after the signing of the Treaty of Almelo. Negotiations towards a model CSA commenced in 1970 under a committee established by the BoG known as the "Safeguards

Committee of 1970," or "Committee 22."[1] The content of the model CSA, designated INFCIRC/153, however, was far more detailed than the safeguards provisions in the Euratom Treaty. While the Euratom Treaty, as mentioned in the previous chapter, guaranteed inspectors access to all places, data and personnel necessary for carrying out its mission (in a similar fashion to the IAEA Statute), the model CSA, which served as an operational interpretation of the IAEA's statutory authority to carry out safeguards, was far more restrictive and specific. Many of these provisions were relevant to GCEP safeguards, and in many cases, States interpreted these measures differently. The following bullet points highlight relevant INFCIRC/153 provisions, conceived in the context of material accountancy verification, that were germane to early GCEP safeguards discussions.

- Paragraph 46(b)(iv): Use of Special Material Balance Areas: INFCIRC/153-type safeguards, unlike Euratom safeguards, offers States the ability to request the designation of special Material Balance Areas (MBAs) for parts of facilities containing commercially sensitive information, with the implication that inspectors would be excluded from these areas. Although this provision was not a point of contention in early discussions on IAEA safeguards for GCEPs, this issue became a topic of debate among the IAEA and technology holders in the late 1970s and early 1980s.

  The origins of the special MBA provision likely grew from efforts by States in Committee 22 to ensure that commercial or industrial secrets would not be compromised via IAEA inspections under CSAs. It is implemented in paragraph 46(b)(iv) of the model CSA, in the

[1] Myron Kratzer, Rich Hooper and Norman Wulf, "A Retrospective of INFCIRCs 153 and 540," Foundations of International Safeguards Series (Pacific Northwest National Laboratory, October 30, 2005), 11.

portion of the document that deals with design information. In this context, it is implicit that the designation of a special MBA would take place during evaluation of a design information initially provided for a facility, as opposed to at a later date, after conclusion of an FA. INFCIRC/153, Paragraph 46(b)(iv) states "If the State so requests, a special material balance area around a process step involving commercially sensitive information may be established."[2] Interestingly, neither the word "special" nor the phrase "special material balance area" are explicitly defined in INFCIRC/153. Thus, even though the provision was likely intended to allow States to prevent inspectors from viewing sensitive or classified technology, there is actually nothing in INFCIRC/153 text itself that sanctions this. Nevertheless, the interpreted meaning of this language, versus the unlimited access provision in the Euratom Treaty (contingent upon necessity of the access), created a fundamental difference between IAEA comprehensive safeguards and Euratom safeguards provisions, in that a possibility existed to restrict the access of IAEA inspectors within declared facilities.[3]

- Paragraph 76(d): Arrangements During Extended Limitations to Inspector Access: INFCIRC/153, Paragraph 76(d) obliges the State and the IAEA, in cases of "extended limitations on access by the Agency" to make special "arrangements with a view to

[2] "The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons," INFCIRC/153 (corrected) (Vienna: International Atomic Energy Agency (June 1972), para. 46(b)(iv).

[3] Very similar language to Article 81 of the Euratom Treaty appears in Article XII.A.6 of the IAEA Statute, which states that inspectors "shall have access at all times to all places and data… as necessary to account for source and special fissionable materials supplied and fissionable products." However, this right is qualified in Article XII.A in that it can only be exercised to the project or arrangement under which the IAEA is applying safeguards. Thus, the implementation of IAEA safeguards is actually governed by the safeguards agreements that the IAEA has in place with its Member States (which draw on the Statute's authority), not directly from the Statute's authority itself. Therefore, limits on IAEA inspector access in a safeguards agreement take precedence over the unlimited access rights in the Statute.

enabling the Agency to discharge its safeguards responsibilities in the light of these limitations."[4] Although it may seem that paragraph 76(d) could be used to support the use of compensatory measures for access restrictions under paragraph 46(b)(iv), the connection between these two provisions is less than clear-cut. There is no explicit language in INFCIRC/153 that links them together. Furthermore, the context of in which paragraph 46(b)(iv) and paragraph 76(d) apply is different. Paragraph 46 applies to the implementation of design information verification (DIV), through which the IAEA defines material balance areas and strategic points to be used to perform routine verification activities. Thus, the designation of a 'special MBA' would take place through DIV.

Meanwhile, paragraph 76 concerns access for inspectors during ad hoc and routine inspection activities. Facility-wide ad hoc inspections typically only take place before an FA has been agreed, and thus before MBAs and strategic points have been defined for a facility. Thus, during an ad hoc inspection, no special or restricted MBA would exist for which the IAEA to compensate with measures under paragraph 76(d). In the case of routine inspections, inspector access is limited to operator records and strategic points specified in the FA.[5] These strategic points would almost certainly not be located within a special MBA designated during DIV by paragraph 46(b)(iv), as these points would be inaccessible to inspectors. Therefore, the limitations on inspector access invoked in paragraph 76(d) would not apply to special MBAs, because special MBAs would be bereft of strategic points to which inspector access (as defined in paragraph 76(c)) could be limited. Following from this argument, paragraph 76(d) would only apply in circumstances where IAEA inspectors

[4] "The Structure and Content of Agreements…," INFCIRC/153 (corr.), para. 76(d).
[5] Ibid., para. 76(c).

had lost access to an area (and the strategic points therein) that had formerly been accessible. Nevertheless, regardless of reasons for invoking paragraph 76(d), the nature of the "arrangements" under the paragraph 76(d) is not specified in INFCIRC/153, thus leaving this to be agreed upon by the State concerned and the IAEA.

- Paragraph 80: Maximum Routine Inspection Effort: INFCIRC/153 contains criteria to be used for determining the actual "number, intensity, duration, timing and mode of routine inspections at any facility,"[6] as well as the maximum routine inspection effort (MRIE), in terms of person-days, that the IAEA can apply. This latter provision is in INFCIRC/153, paragraph 80. The language contained in paragraph 80 leads to some ambiguity when applied to enrichment safeguards. For facilities other than reactors or sealed storage facilities that handle more than 5 effective kilograms of nuclear material per year, MRIE depends on whether processes use plutonium or uranium in excess of 5% enrichment, as well as the quantity of material contained at a facility. MRIE for facilities "involving" plutonium or greater than 5%-enriched uranium is defined in paragraph 80(b) as $30\sqrt{E}$ person-days per year (up to an absolute maximum of 1.5 person-years of inspection per year), where *E* is a facility's annual throughput of nuclear material defined in effective kilograms.[7] A generally lower MRIE limit, defined in paragraph 80(c), applies for facilities that do not involve plutonium and handle less than 5%-enriched uranium, which is defined

[6] Ibid., para. 81.
[7] Ibid., para. 80(b). From INFCIRC/153, para. 104, effective kilograms (*E*) are defined in the following manner for uranium, where x is enrichment and m is uranium mass:
$x \leq 0.005$: $E = 0.00005m$;
$0.005 < x < 0.01$: $E = 0.0001m$;
$x \geq 0.01$: $E = mx^2$

as $100 + 0.4E$ person-days per year.[8] The word "involving," certainly does not indicate that plutonium or higher-enriched uranium must be continuously present at a facility in order to trigger the higher MRIE provision—there is a strong argument that facilities that handle this material, even occasionally, would be subject to the higher MRIE, as their operations would *involve* the higher-risk material. However, this language is vague concerning an enrichment facility only producing less than 5%-enriched material, but if modified, can produce material in excess of 5% enrichment. Operation of the enrichment plant, as declared, would *not* involve uranium enriched higher than 5%, even though the plant has the capability to produce this material. At the time INFCIRC/153 was drafted, consensus did not exist on which MRIE formula to apply to enrichment plants.

Revising Classification Policy

As noted in the previous chapter, classification policy for centrifuge technology was a key factor as States determined their positions on GCEP safeguards. Although the highly restrictive 1960 Quadripartite Classification Guide was still in place as States began this work, by 1971, the Troika had started working on a new, more nuanced classification guide that would allow for the "economic necessities" of operating industrial-scale GCEPs.[9] Mass-producing centrifuge components, for example, would require larger numbers of personnel than a centrifuge R&D program, and giving all of these workers high-level security clearances would be impractical, or even unnecessary, for workers responsible for manufacturing less-sensitive parts. Information on

[8] Ibid., para. 80(c).
[9] Original German: "wirtschaftliche Notwendigkeiten," Auswärtiges Amt to FRG Embassy Washington, "Geheimhaltung der Gaszentrifugen-Technologie," BArch, B 196/10390 (February 1, 1973), 1.

plant operating costs and capacities would need to be available for sharing, in order for Urenco to win over customers. In May 1971, Frank Panton, of the UK Ministry of Defence, suggested that the UK broach the subject in its response to General Crowson's request for U.S.-UK bilateral talks on enrichment safeguards.[10] However, in response to this proposal, the UK Atomic Energy Authority (UKAEA) noted that it was not in Crowson's capacity to discuss classification issues, and so raising the issue would not be productive.[11]

The first quadripartite meeting on centrifuge technology classification took place in The Hague in May 1972. Records indicate that U.S. and Troika positions aligned fairly closely at this meeting. All parties agreed that economic information on centrifuge technology should be unclassified, as well as "conventional components and conventional manufacturing techniques," as long as classified technical details were not revealed.[12] Furthermore, instead of blanketing a classification level of "Secret" on essentially all centrifuge and cascade technology, classification of items would be applied on a graded approach.[13] A draft classification guide prepared by the Troika in May 1972, for example, provided for a classification level of 'Restricted' for manufacturing specifications and processes using finished centrifuge components that did not reveal sensitive technology.[14] Information or technology classified as "Restricted," the lowest classification level, could be handled by uncleared personnel in the Troika States.[15] The parties also agreed that the

[10] F.H. Panton to R. Press, "Uranium Enrichment: Safeguards," TNA FCO 55/760/18 (May 5, 1971).
[11] J.L. Croome to R. Press, "Uranium Enrichment Safeguards," TNA FCO 55/760/22 (May 10, 1971).
[12] Tripartite ad hoc Committee on Classification, "Report to Joint Committee on Classification of Centrifuge Project," JC/ClS af 72/3, PA AA, B 72 (ZA)/105295 (The Hague, May 29, 1972), 1-2.
[13] Ibid., 2.
[14] Tripartite Joint Committee, "Classification Guide for the Tripartite Centrifuge Programme," PA AA, B 72 (ZA)/105295 (May 17, 1972), 3.
[15] Tripartite Joint Committee, "Classification Difficulties in Centrifuge Production: Paper for Centrifuge Joint Committee Meeting on 5 June 1974," JC/UK/74/4, BArch, B 196/10390 (May 29, 1974), 3.

new guide could be a tripartite guide, instead of a quadripartite guide, although the Troika States committed to inform the United States of any significant changes in centrifuge technology classification.[16] The Tripartite Joint Committee (JC) approved a new classification guide in January 1973. The finished guide indeed reflected the more light-handed approach that had been agreed with the United States the previous year. A comparison of classification levels for information under the 1960 and 1973 Classification Guides is given in Table 4-1.

[16] Tripartite ad hoc Committee on Classification, "Report to Joint Committee on Classification of Centrifuge Project," JC/ClS af 72/3, PA AA, B 72 (ZA)/105295 (The Hague, May 29, 1972), 2.

Table 4-1: Comparison of classification levels for information specified in the 1960 and 1973 Classification Guides. Sources: U.S. Atomic Energy Commission, "Gas Centrifuge Classification Guide" (1960); Tripartite Joint Committee, "Tripartite Centrifuge Programme Classification Guide," BArch, B 196/10390 (January 17, 1973).

Key to classification levels: S=Secret, C=Confidential, R=Restricted.

Information	1973 Class. Level	1960 Class. Level
A. Centrifuge Machines		
1. Comprehensive specification or description of production, prototype and other machines which have been under study in the period since 1st August 1960, or are currently under study.	**S**	**S**
2. Analysis of performance (including output and separative performance) of the machines in (1) above, and comparison with experiments, (except as provided in (3) below).	**C**	**S**
3. Information revealing sensitive centrifuge technology, such as a. peripheral velocity b. engineering specifications of rotor tubes, end caps, baffles, bearings, molecular pumps, feed pipe assemblies, scoops.	**S**	**S**
4. Engineering specifications of specifically developed centrifuge components capable of revealing centrifuge design and performance other than those listed in (3.b) above	**C**	**S**
5. Manufacturing specifications and manufacturing processes for the finished centrifuge components listed in (3.b) above, and which do not reveal sensitive centrifuge technology. (Those which do reveal sensitive centrifuge technology should be classified according to the technology revealed).	**R**	**S**
6. Manufacturing specification and manufacturing process for the finished centrifuge components other than those listed in (3.b) above are classified only if they reveal classified centrifuge information, in which case they are classified according to that information.	**Variable**	**S**
B. Centrifuge Plants		
1. Comprehensive specification or description of centrifuge plants which have been under study in the period since 1st August 1960, or are currently under study.	**S**	**S**
2. Details of cascade performance, operating characteristics and control methods in relation to specific designs of enrichment plants.	**C**	**S**

Information	1973 Class. Level	1960 Class. Level
3. Subject to (1) and (2) above, cascade and installation unit specifications, provided neither the machine specification nor any part thereof, nor the layout of the cascade or the manner in which the machines are mounted or interconnected, is thereby revealed.	**R**	**S**
4. Engineering and manufacturing specifications of plant components specifically developed or specifically modified for enrichment plants should be classified in accordance with the technology they reveal.	**Variable**	**S**
5. Methods of controlling process materials.	**R**	**S**
6. Chemical effect of UF_6 on materials and components; consequent modifications made to commercially available equipment.	**C**	**S**
C. Research and Development Research and development work should be classified in accordance with the corresponding classification in A and B above.	**Variable**	**S (generally)**
D. Economics Economics of plant performance, costs and plant capacities are classified only if they reveal classified centrifuge information.	**Variable**	**S**

Immediately after approval of the new 1973 classification guide, work began on a more detailed Tripartite Classification List, which specified classification levels of individual technologies and information, on the basis of the updated classification guide. General agreement was reached on this list by early 1974,[17] despite some disagreements between technology holders (most notably on the classification level of rotor tubes prior to the installation of end caps and baffles).[18] While the

[17] Tripartite Joint Committee, "Minutes of the 12th Meeting held in London on 28 March 1974," JC/SEC/74/4, BArch, B 196/10388 (March 28, 1974).

[18] In this case, a disagreement arose between German manufacturers, who desired a classification level of 'Restricted' for unfinished rotor tubes, while Dutch and British manufacturers viewed 'Confidential' as the appropriate level. At the time the classification list was being drafted, the German industrial conglomerate MAN was using uncleared foreign workers to machine centrifuge rotor tubes in a non-secure manufacturing area. While arguments were made that downgrading the classification of rotor tubes in the Netherlands and

1973 classification guide simplified the centrifuge manufacturing process, while also allowing Urenco to become far more transparent about the economics of GCEP operation, this new classification guide did not provide much help regarding potential access of safeguards inspectors to sensitive information inside cascade halls. Under the new classification guide, inspectors could still be exposed to information classified 'Confidential' or above upon entering cascade areas, which typically could not be disclosed to uncleared foreign nationals. Information on specific cascade configurations, for example, could be classified as 'confidential' under paragraph B.2 of the guide. Separative performance values for centrifuges were classified 'confidential' as well (paragraph A.2), and along this vein, even the approximate length of centrifuges was considered classified at the time.[19] Nuclear material accountancy data, in combination with an estimate of the number of centrifuges in a facility, can be used to estimate the separative capacity of individual centrifuges. Furthermore, the prerogative remained, under the context of INFCIRC/153-type safeguards, for GCEP operators to deem any technology (regardless of security classification) to be commercially sensitive.

The relaxation of classification rules for GCEP technology in the early 1970s was borne out of necessity. Under the rules imposed by the 1960 Quadripartite Classification Guide, constructing

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the UK would harm nonproliferation efforts, it was also noted that hiring and clearing new staff at MAN to handle 'confidential' information would take nearly a year, and delay construction activities at Almelo. This situation did not fully resolve until 1976, when the rotor tube design for the new G3 centrifuge (also manufactured by MAN) was classified 'confidential.' See: Tripartite Joint Committee, "Classification Difficulties in Centrifuge Production: Paper for Centrifuge Joint Committee Meeting on 5 June 1974," JC/UK/74/4, BArch, B 196/10390 (May 29, 1974); Karl Keltsch, "Consequences of higher classification of rotor tubes (see no. 3.5 of draft classification list) at MAN in Munich," BArch, B 196/10390 (September 17, 1974); Tripartite Junior Joint Committee, "Minutes of a Junior Joint Committee Meeting held in Bonn on 20 February 1976," PA AA, B 72 (ZA)/119508/491.23/SB6 (February 20, 1976).

[19] W.E. Fitzsimmons to A.J. van Galen Last, "Classification of Enrichment Technology – Discussions with the United States," PA AA, B 72 (ZA)/123660/491.23/1 (October 25, 1978).

and operating industrial-scale commercial GCEPs would have been grossly impractical, and it would have been clear to all stakeholder governments that this was the case. Disagreements on classification issues, in particular between the United States and the Troika, were rare. The new 1973 classification rules, however, were not compatible with unlimited access for safeguards inspectors for foreign nationals.

By contrast, on the issue of GCEP safeguards—particularly misuse—disagreements abounded. Although all parties agreed, at the time, that inspector access to cascade areas was to be restricted, the U.S. and Troika positions shared little else in common. The following sections describe the formation of the initial U.S. and Troika positions.

Initial Stakeholder Positions

The U.S. Position

In the early 1970s, the United States developed an intricate perimeter-based surveillance concept to address the perceived need at the time to restrict inspector access to sensitive parts of facilities. Fundamentally, under this system, a fenced-off area would be set up around an enrichment facility, through which flows of nuclear material would be measured. Personnel and equipment crossing the perimeter would also be checked, in order to ensure the absence of clandestine flows of material in and out of the plant, and the absence of over-enrichment of material—i.e. the absence of facility misuse. Within the perimeter, an exclusion area would be set up, to which inspector access would be prohibited.

The roots of the initial U.S. position stretch back to the 1968 Union Carbide enrichment safeguards report mentioned in the previous chapter.[20] Even though the authors of the report considered access to all areas of a GCEP to be necessary to obtain all material balance information (even though the amount of in-process material in a GCEP is typically very low),[21] the authors still proposed perimeter access as a possible alternative. Under this system, an inspectorate would verify flows of material (and in this paper, electrical power) in and out of an exclusion area, while not making any measurements inside the area itself. As classification restrictions precluded the access of inspectors to all areas of enrichment plants, the perimeter safeguards concept became an attractive option to the U.S. safeguards community over the coming years. Furthermore, a perimeter safeguards system would not only provide assurance of the non-diversion of declared nuclear material, but also of the absences of over-enrichment of material and of undeclared material at a facility, as all nuclear material entering and exiting the plant would be verified. This concept was applied to both diffusion and centrifuge enrichment safeguards. However, following a 1969-1970 study, the USAEC Advisory Committee on Nuclear Materials Safeguards concluded that a perimeter safeguards system with surveillance only applied at the site boundary of an enrichment plant would be inadequate, and that additional inspector access (i.e. a smaller exclusion area) would be required.[22] A U.S. paper on gaseous diffusion plant safeguards, shared with the UK in preparation for bilateral talks in early 1972, considers four levels of access in addition to controls at a facility's perimeter. In increasing order, these levels were access up to the facility perimeter

[20] J.F. Hudson and W.D. McCluen, *Safeguards Inspection for Centrifuge and Gaseous Diffusion Plants*, Report Number K-P-3559, Union Carbide Corporation, TNA FCO 55/760 (July 24, 1968).
[21] Ibid., 5.
[22] H.D. Bengelsdorf, "Safeguarding Enrichment Plants," Draft Paper, U.S. Atomic Energy Commission, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 21, AE 13: Safeguarding Enrichment Plants, 1972 (February 14, 1972), 2–3.

fence, access up to the building exterior, access up to the housings of separation units, and access within the housings of separation units (but not to the interiors of separation units, decontamination areas, or control areas).[23] A near-identical concept was applied by the United States to GCEP inspector access. The paper prepared by the United States in preparation for the first round of quadripartite GCEP safeguards talks, which would take place in April 1972, is almost identical in structure to the American gaseous diffusion safeguards paper. The American GCEP safeguards paper's four access levels, in increasing order, are: access up to the facility perimeter fence, access up to the building exterior, access "up to the walls of the enclosures containing separative units," and access up to the centrifuge casings and cascade piping.[24] The GDP and GCEP papers prepared by the United States bear remarkable similarities: not only is the outline of each paper essentially identical, entire paragraphs, including those describing the perimeter control system, are identical in both papers.[25]

While the rationale behind the GCEP perimeter safeguards concept was shared with GDP safeguards, however, the U.S. Government did dedicate some effort to developing a nuanced safeguards approach that was specific to GCEPs. An internal USAEC paper prepared by Hal Bengelsdorf, Assistant Director of the USAEC Division of International Security Affairs (ISA) reveals some debates that took place within the USAEC on the issue, in preparation for the June

[23] U.S. Atomic Energy Commission, *An Analysis of Safeguards Inspections at Gaseous Diffusion Plants*, TNA FCO 55/963 (January 10, 1972), 6–8.
[24] U.S. Atomic Energy Commission, *An Analysis of Safeguards at Gas Centrifuge Plants*, TNA FCO 55/964 (March 24, 1972), 2.
[25] Compare paragraphs 1.2.3 – 1.2.5 in the USAEC GDP paper to paragraphs 1.3.2 – 1.3.4 in the USAEC GCEP safeguards paper.

1972 IAEA Technical Working Group, and the quadripartite meetings that preceded it.[26] From this paper, it is clear that there was consensus that the access of inspectors to GCEP cascade areas should be limited to some degree. The optimal amount of inspector access, however, with respect to safeguards effectiveness versus information protection, was a disputed matter within the U.S. Government. Of the four levels of access considered in the USAEC's GCEP safeguards paper, the second and third options were viewed most favorably. In the second option, with access up to a building's exterior (assuming that UF_6 cylinders were stored outside), inspectors could verify the amounts and assays of material at the "feed and takeoff points,"[27] which would presumably be where UF_6 cylinders would enter and leave the building. With this information, in conjunction with the monitoring of vehicle and personnel traffic through the facility's perimeter, an inspectorate could effectively verify material accountancy. However, this approach would do little to verify the absence of clandestine activities inside an enrichment plant, particularly if an operator were to use secret feed and takeoff points, perhaps via buried pipes, which would be difficult to non-intrusively detect.[28] In this case, a malicious operator could produce weapons-usable material using undeclared feed and store it inside the enrichment plant indefinitely. This motivated support for the third access option, which would allow for inspector access to the interior of a plant, up to the exterior of the process areas. Under this approach, the USAEC envisioned that inspectors could perform NDA measurements on pipes leaving or connecting process areas to ensure the absence of over-enrichment, and visually verify the absence of undeclared enrichment capacity inside the building.[29] This approach was favored by USAEC-ISA, the USAEC Division of Nuclear Materials

[26] H.D. Bengelsdorf, "Safeguarding Enrichment Plants," Draft Paper, U.S. Atomic Energy Commission, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 21, AE 13: Safeguarding Enrichment Plants, 1972 (February 14, 1972).
[27] Ibid., 4.
[28] Ibid., 5.
[29] Ibid., 6–7.

Security, and the U.S. Arms Control and Disarmament Agency (ACDA).[30] The USAEC Division of Classification, however, argued that the additional assurance gained in the latter approach was not worth the added risk of disclosing classified information through expanded inspector access.[31] At the time the U.S. GCEP safeguards report was drafted, however, it should be noted that the 1960 Quadripartite Classification Guide was still in effect. Thus, the USAEC's Division of Classification reported that even access up to the feed and takeoff points would reveal some classified information of "limited significance,"[32] although again, under the 1960 guide, even the SWU capacity of a GCEP would have been considered classified. Clearly, the exposure of more sensitive information, such as material loss rates (although safeguards-relevant) and cascade isotopic gradients, would result from the approach featuring a higher level of inspector access.

Because of its internal disagreement regarding the acceptable degree of inspector access, the United States did not specify a degree of inspector access that it favored during its consultations with the Troika or with the IAEA. Instead, on the presumption that access would be limited in some way, the United States focused more on advocating for a perimeter safeguards concept in order to compensate for these access limitations. The resources required for implementing this concept, which entailed round-the-clock monitoring of every person and item entering and leaving the exclusion area, were enormous. The U.S. GCEP safeguards paper, as delivered to the UK, acknowledged that all personnel, vehicles, and packages crossing the secured perimeter would need to be monitored.[33] The amount of inspection effort required for constantly manning and

[30] Ibid., 12.
[31] Ibid., 9.
[32] Ibid., 7.
[33] U.S. Atomic Energy Commission, *An Analysis of Safeguards at Gas Centrifuge Plants*, TNA FCO 55/964 (March 24, 1972), 54.

maintaining a single perimeter portal, as shown in Table 4-2, exceeded the paragraph 80(c) MRIE limit for enrichment facilities of all sizes, and even exceeded the higher paragraph 80(b) MRIE limit for smaller facilities. However, the United States interpreted INFCIRC/153, paragraph 76(d) to mean that MRIE limits could be exceeded in cases where inspector access was limited for classification reasons.[34] Effectively, the U.S. interpretation was that the "arrangements" called for in paragraph 76(d), given "extended limitations on access," would be non-application of the MRIE limits in paragraph 80. This would render moot the question of which MRIE formula should be used for calculating maximum allowable inspection effort at a GCEP, since under the U.S. interpretation, MRIE would not apply at all. Thus, from the U.S. perspective, the inspection effort implicated in its perimeter safeguards system was consistent with the text of INFCIRC/153.

Table 4-2: Comparison of actual inspection effort figures under the USAEC perimeter safeguards system versus INFCIRC/153 MRIE figures. Assumed material production rates, in effective kilograms over SWU capacity, are provided for the USAEC's INFCIRC/153 MRIE calculations. Source: U.S. Atomic Energy Commission, "Summary of the Washington Meeting on Safeguards in Gas Centrifuge Plants, U.S.-Tripartite Centrifuge Consortium, April 19-20, 1972" Appendix B, BArch, B 196/10391 (May 9, 1972); corrected in Tripartite Joint Committee, "Minutes of the quadripartite meeting on safeguarding of centrifuge enrichment plants," PA AA, B 72 (ZA)/114137 (May 25, 1972).

Facility Capacity (tSWU/yr)	INFCIRC/153 MRIE (person-days/yr)		USAEC-proposed Average Routine Inspection Effort (person-days/yr)	
	80(c) *0.3 ekg/tSWU*	80(b) *4.2 ekg/tSWU*	Minimum (1 portal)	3 portals
100	112	615	1207	4492
350	142	1148	1237	4522
1000	221	1942	1316	4601
4000	585	3882	1680	4965

[34] H.D. Bengelsdorf, "Safeguarding Enrichment Plants," Draft Paper, U.S. Atomic Energy Commission, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 21, AE 13: Safeguarding Enrichment Plants, 1972 (February 14, 1972), 13.

Another key element of the U.S. GCEP safeguards approach, as well as the U.S. GDP safeguards strategy, was the use of the Minor Isotope Safeguards Technique (MIST).[35] MIST would measure the abundance of minor uranium isotopes in material flowing through process areas to verify the non-diversion of declared material and non-introduction of undeclared material in process areas. During the enrichment process, the concentration of minor isotopes in uranium changes continuously along with that of ^{235}U. Under normal operation of an enrichment plant, the concentrations of minor isotopes, as well as their ratios to the ^{235}U concentration (e.g. $^{234}U/^{235}U$ and $^{236}U/^{235}U$ ratio, if applicable[36]) will be consistent with their expected values at feed and withdrawal points. However, if equipment is not being operated as declared – for example, if a clandestine cascade fed by a declared cascade exists inside a plant, with the tails from the clandestine cascade serving as declared product – the minor isotope ratios will be inconsistent with the declared information.[37] Mass spectroscopy measurements on samples taken at the feed and withdrawal points would reveal this discrepancy.[38] MIST, however, was essentially a paper concept at the time, and the United States, of course, had no commercial-scale GCEP in which to test MIST. A report on the first MIST test[39] at the Oak Ridge K-25 plant would not be issued until April 1973, more than a year after the UK received the U.S. GCEP safeguards concept paper.

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[35] U.S. Atomic Energy Commission, *An Analysis of Safeguards at Gas Centrifuge Plants*, TNA FCO 55/964 (March 24, 1972), 57.

[36] In some MIST tests, feed material was spiked with ^{236}U, which could serve as a way of verifying the absence of undeclared feed and takeoff points as well. See "MIST III Experiment," SK/10/02, TNA FV 70/14 (April 1, 1976).

[37] In this case, since ^{234}U is separated more efficiently from ^{238}U, owing to its greater mass difference, the concentration of ^{234}U in the "product" of the declared cascade (actually the tails of the clandestine cascade) would be too low. Some amount of ^{234}U would end up in the product of the clandestine cascade, which would otherwise have ended up in the legitimate declared product, had the plant been operated as declared.

[38] S. Blumkin and E, Von Halle, "A Preliminary Report on the Minor Isotopic Measurements; MIST Test II," K-OA-2388, Annex I in J.E. Ellingsen, "Note for the Record: Meeting to discuss the Minor Isotopes Safeguards Technique (MIST) and its application to enrichment plants held in Room 1563, Thames House South on Monday, 10 December 1972," TNA FV 70/14/24 (December 14, 1973).

[39] Ibid., 3–4.

In many aspects, the U.S. position on GCEP safeguards relied on unproven technology. In addition to MIST requiring further development and testing, portal-screening devices for vehicles and packages did not yet exist in fieldable form in the early 1970s. The 1972 U.S. GCEP safeguards paper proposed the use of active gamma interrogation to detect undeclared material in vehicles and packages,[40] since passive gamma detection methods could be thwarted with lead shielding. In short, the U.S. position reflected a great deal of optimism, with respect to the development of new safeguards devices and techniques.

The Troika Position

The GCEP safeguards concept initially put forth by the Troika, in contrast with the approach proposed by the United States, adhered more strictly to INFCIRC/153 provisions on inspector effort, while treating the possibility of facility misuse with far less urgency. In addition, the Troika approach was much more conservative in its consideration of new safeguards methods, instead depending on standard techniques for material balance verification.

While this approach was presented to both the IAEA and Euratom in 1972 as a coordinated position of the three States, the substance of the Troika concept was essentially British. The roots of this approach came from a 1968 paper authored by Frank Morgan, of the UK Atomic Weapons Research Establishment (AWRE), and Duncan Janisch, which was updated by Morgan and

[40] U.S. Atomic Energy Commission, *An Analysis of Safeguards at Gas Centrifuge Plants*, TNA FCO 55/964 (March 24, 1972), 97.

Howard Hughes,[41] of British Nuclear Fuels, Ltd. (BNFL), which had recently been spun off from the UK Atomic Energy Authority (UKAEA). While the draft by Morgan and Hughes explicitly deals with GCEP safeguards, it is unclear wehtehr the original Morgan and Janisch paper dealt with GDP safeguards, or enrichment safeguards more generally. While the first sentence of the Morgan and Hughes draft indicates that it was adapted from the Morgan and Janisch paper, the following sentence introduces the perimeter safeguards concept in the context of GDP safeguards.[42] However, the paper does not endorse or go into much depth on the perimeter safeguards concept, as it would apply to GCEP safeguards.[43] In any case, Morgan and Hughes argue that the accuracy of weight and isotopic measurements, along with the low process inventory of GCEPs, would allow for an effective safeguards system based only upon weighing and sampling of material at declared feed and takeoff points, undertaken on a random basis.[44] MIST is considered in the paper, but only as a means for resolving abnormal issues, such as instances in which large amounts of material are unaccounted for.[45] Modifications to cascades to produce higher-than-declared enrichment levels are deemed to be practically infeasible, and Morgan and Hughes argue instead that a state would more likely use an undeclared GCEP to produce weapon-usable material.[46] The paper takes a strict interpretation of the MRIE levels given in INFCIRC/153,

[41] F. Morgan and H.A. Hughes, "The Safeguarding of Centrifuge Plants," SSCD/71/68 (March 29, 1971), attachment to F. Morgan to H. Hughes, SSCD/71/73, TNA FCO 55/760/12 (March 31, 1971).
[42] Ibid., 1.
[43] The 1971 Morgan and Hughes paper does state that GDP safeguards is challenging, as a result of the associated large in-process inventories, and large measurement uncertainties that would result from this. Within this context, it could be inferred that the perimeter safeguards concept was meant to mitigate unacceptably large uncertainties for process inventories encountered inside GDPs by ensuring that material, if diverted, would not be able to leave the premises without being detected. Morgan and Hughes' observation that process inventories in GCEPs are extremely small (Ibid., 2–3) would imply, perhaps, that a perimeter system would not be necessary for GCEP safeguards.
[44] Ibid., 5.
[45] Ibid., 3.
[46] Ibid., 3–4.

applying the lower paragraph 80(c) limit to plants declared to be producing less than 5%-enriched material.[47]

The Morgan and Hughes paper also touches upon the issue of sensitive information that could be disclosed to inspectors, noting efforts should be made to "avoid" the access of inspectors to cascade areas, and "access to assembly and maintenance workshops seems quite unnecessary."[48] This language, however, was strengthened as the paper underwent review by stakeholder organizations in the British government. A revision by the UKFCO suggested, regarding cascade access, that "ways must be found to make this unnecessary," and "access to assembly and maintenance workshops cannot of course be required."[49]

By early May 1971, after the FCO's revisions had been incorporated, the Morgan and Hughes paper had been edited by Jack Parry of BNFL, who was responsible for centrifuge research and development at BNFL's Capenhurst plant. Parry was to become Urenco's first Technical Manager upon the company's incorporation in September 1971.[50] The new paper came with two new appendices. The first contained a suggested list of design information to be provided to the safeguards inspectorate, and the second appendix listed methods for ^{235}U accounting. The design information appendix is notably generic, including nothing more detailed than a very rough layout of the plant, as shown in Table 4-3. At this stage, Hughes suggested that the amended paper serve as a basis for talks with the Netherlands and the FRG, whose stakeholder organizations would need

[47] Ibid., 4.
[48] Ibid., 1.
[49] M.J. Newington to F. Morgan, "Safeguarding of Centrifuge Enrichment Plants," TNA FCO 55/760/13 (April 20, 1971).
[50] R.B. Kehoe, *The Enriching Troika: A History of Urenco to the Year 2000* (Marlow, UK: Urenco Limited, 2002), 41, 46.

to approve of its content before GCEP safeguards discussions with the United States could take place.[51]

Table 4-3: GCEP Design Information to be provided to a Safeguards Inspectorate, as proposed in the Parry revision to Morgan and Hughes, May 1971. Source: "The Safeguarding of Centrifuge Plants," attachment to H.A. Hughes to F. Morgan, TNA FCO 55/760/21 (May 3, 1971).

Information and design data to be provided to the Safeguards Inspectorate (Parry, May 1971)	
(i) Name	(x) Layout of plant, including containment and access routes and showing incoming and outgoing nuclear material storage areas, cascade, laboratory waste disposal facilities.
(ii) Location	
(iii) Owner (legally responsible body)	
(iv) Operator (legally responsible body)	
(v) Present status of enrichment plant	
(vi) Construction schedule (start of construction, start of commissioning, start of operation)	(xi) Special information of importance to safeguard inspectors. (Organisational responsibility for material control and routine contact with the inspecting organisation, name and time. Health and Safety regulations with which the inspectors should comply at the plant).
(vii) Purpose and type of enrichment plant	
(viii) Operating mode of enrichment plant (continuous or batch)	
(ix) Layout of plant site (map showing perimeters and premises of facility, buildings, roads, rivers, railways, etc.)	

Although a further revised version of the Morgan and Hughes paper was transmitted by the UKAEA to the UK Cabinet Office for review,[52] this document was not passed on for consideration by the UK's partners. Instead, a new paper authored by Jack Parry, extensively derived from Morgan and Hughes, served as the basis for discussions. This new paper was drafted as a Urenco

[51] H.A. Hughes to F. Morgan, TNA FCO 55/760/21 (May 3, 1971).
[52] F. Morgan, H.A. Hughes, and J.V.L. Parry, "The Safeguarding of Centrifuge Plants," attachment to UK Atomic Energy Authority, "The Safeguarding of Centrifuge Plants: Note by the Atomic Energy Authority," TNA FCO 55/760/27 (May 18, 1971).

paper (on Urenco stationery) in the summer of 1971,[53] presumably in anticipation of the company's incorporation. The content in Parry's new paper, however, was very close to that in Morgan and Hughes' work. To illustrate the similarities between the two papers, both appendices from Parry's revision of Morgan and Hughes appeared in the newer paper, and although the substance of the two papers differs slightly, the conclusion of the Parry Paper is analogous to the latest Morgan and Hughes version that preceded it. The Morgan and Hughes conclusion paragraph reads:

> "Input-output monitoring of UF6 on a random basis, with access confined to the feed and take-off points and to their associated traps, is an adequate means of international control. The manpower requirement falls within the maximum units permissible to the IAEA under the draft Safeguards Agreement."[54]

For comparison, the new Parry Paper's conclusion states:

> "IAEA inspection of the input-output monitoring of the plant as described above, with inspectorate access confined to the input-output stations and the associated vessels and other plant items external to the cascade area, is an adequate means of international control of the use of centrifuge plants. Such arrangements can be readily accommodated by the

[53] J.V.L. Parry, "The Safeguarding of Centrifuge Plants," July 6, 1971, attachment to F. Morgan to M.J. Newington, SSCD/71/166, TNA FCO 55/760/55 (July 27, 1971).
[54] F. Morgan, H.A. Hughes, and J.V.L. Parry, "The Safeguarding of Centrifuge Plants," attachment to UK Atomic Energy Authority, "The Safeguarding of Centrifuge Plants: Note by the Atomic Energy Authority," TNA FCO 55/760/27 (May 18, 1971).

owners and operators of the plants without divulging any information which, for security reasons, may be sensitive."[55]

Other key elements of Morgan and Hughes, such as the lower MRIE limit and the assessment that GCEP misuse is unlikely, are reflected in the new Parry Paper, with the texts again bearing remarkable similarities.[56] Nevertheless, Parry introduced new presentational elements in his draft. In particular, the new version established four explicit principles for GCEP safeguards that were carried forward into the draft that was approved by Urenco. The first was that access to centrifuges or cascades was not necessary for inspectorates (apparently with reference to material accountancy), because of the low inventory of material inside cascades. Parry estimated that a centrifuge contained on the order of 100 mg of uranium, so a 100,000-centrifuge plant would only carry on the order of 10 kg of material in its cascades. Under normal operating conditions, this mass of material would correspond to less than one effective kilogram and could be neglected for safeguards purposes.[57] Furthermore, cascade hall access by inspectors was undesirable, as it would put sensitive information at risk. Parry's second principle follows from the first, in that material balance would be established through measurement at input and output points to the plant, and not inside the plant. Third, Parry noted that the majority of process inventory in a centrifuge plant would be material in "intermediate vessels between the cascade or cascades and the input and output stations."[58] These vessels were desublimer tanks, which were used in early Troika cascade

[55] J.V.L. Parry, "The Safeguarding of Centrifuge Plants," July 6, 1971, attachment to F. Morgan to M.J. Newington, SSCD/71/166, TNA FCO 55/760/55 (July 27, 1971).
[56] Ibid., 3–4.
[57] For uranium enriched in excess of 1%, the IAEA defines mass in effective kilograms as the actual mass of the uranium times the square of its enrichment. See "The Structure and Content of Agreements…," INFCIRC/153 (corr.), para. 104(b).
[58] J.V.L. Parry, "The Safeguarding of Centrifuge Plants," July 6, 1971, attachment to F. Morgan to M.J. Newington, SSCD/71/166, TNA FCO 55/760/55 (July 27, 1971), 2.

designs for collecting product and tails material from cascades before transferring it into transport cylinders. Under Parry's plan, inspectors would be allowed to view the tanks, but would be prohibited from directly measuring their contents, or flow rates into or out of the tanks. Fourth, Parry argued that plant mass balance records (including process inventory estimates) could be used to supplement an inspectorate's input and output measurements. A representation of the Parry system, showing sampling and weighing points, the boundary of the cascade 'black box,' as well as the boundary of the mass balance for the facility, is given in Figure 4-1.

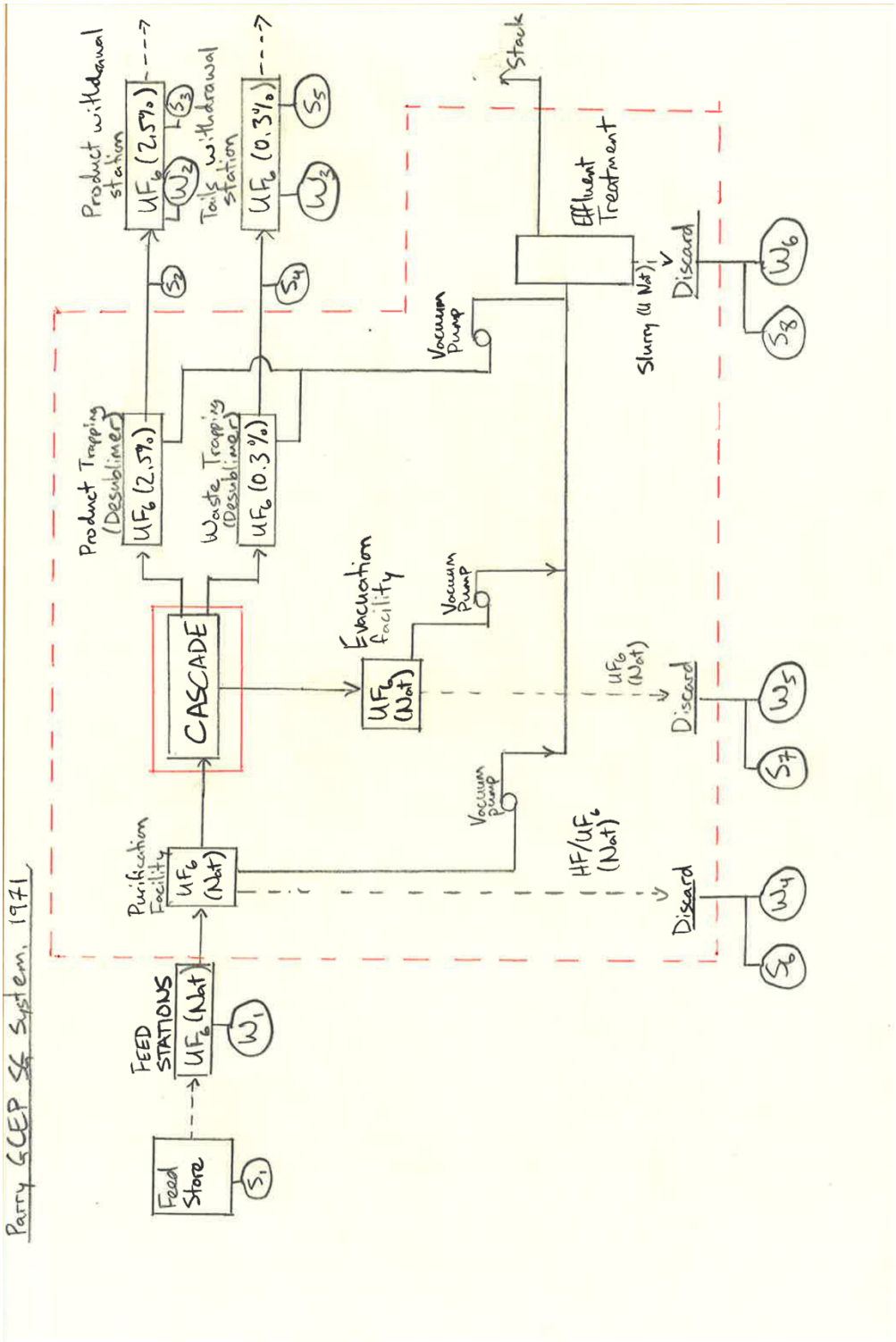

Figure 4-1: Schematic of the GCEP safeguards system presented in the Parry Paper. The solid red line denotes the boundaries of the 'black box' in which inspector access would be prohibited. The dashed red line shows the boundary of the process material balance area. The labels S2 and S4 denote sampling points for the product and tails lines, respectively, while S1, S3, and S5-S8 denote the sampling of material from containers. The labels W1-W6 indicate where containers are to be weighed. Source: J.V.L. Parry, "The Safeguarding of Centrifuge Plants," July 6, 1971, attachment to F. Morgan to M.J. Newington, SSCD/71/166, TNA FCO 55/760/55 (July 27, 1971), Appendix III.

In sum, the Parry system constituted a minimalist approach to GCEP safeguards. A tacit assumption behind Parry's proposal (although this assumption would become more explicit in later Troika positions) was that the sole purpose of safeguards was to verify the non-diversion of declared nuclear material at a facility. As in Morgan and Hughes, material balance at the periphery of a GCEP's process area would suffice in achieving this objective, without risking the leakage of sensitive centrifuge and cascade information, and without encumbering facility operations. To some officials in the UK Government, the production of this paper established a clear stance and anchor point for GCEP safeguards negotiations for itself and its partners, grounded in the legal framework provided by INFCIRC/153, which could be used to resist pressure from other States, especially the United States and Soviet Union, to accept stricter safeguards measures. Mike Newington, a UK Foreign & Commonwealth Office (UKFCO) official heavily involved with GCEP safeguards policy at the time, articulated in a letter written in the aftermath of the U.S.-FRG meeting at Karlsruhe, "there is an obvious risk of the Americans and the Russians "ganging up" to urge the imposition of unnecessarily stringent safeguards on centrifuge plants, and we have to defend our interests as best we can."[59] In a following paragraph, Newington then wishes for the speedy transmission of Parry's paper to the other Troika governments.[60] By late 1971, the UKFCO was acutely aware of the U.S. position on MRIE and compensatory measures for inspector access limitations in the context of diffusion safeguards, advising the UK Cabinet Office of the need to avoid accepting these principles in the realm of GCEP safeguards.[61] With this dynamic in mind,

[59] M.J. Newington to Arculus and Rose, "Safeguards on Uranium Enrichment Plants," TNA FCO 55/760/67 (August 20, 1971).
[60] Ibid.
[61] M.J. Newington to R. Press, "Safeguards on Uranium Enrichment Plants," TNA FCO 55/761/101 (December 17, 1971).

the production and acceptance of a British paper (and subsequently a Troika paper) on GCEP safeguards gained added importance.

There is no explicit evidence for why the Morgan and Hughes draft was reworked and then represented as Parry's work. It seems likely however, that UK Government would have preferred that its desired position on GCEP safeguards be implanted from within Urenco by a soon-to-be Urenco employee, rather than externally from the UKAEA or BNFL. There are some indications in archival material that imply that the British Government sought somewhat to cover its tracks in introducing the new Parry Paper to Urenco. Frank Morgan,[62] in a then-classified letter accompanying the Parry Paper to Mike Newington, instructed Newington not to broadcast the fact that he had received a copy from Morgan.[63] Parry submitted the paper to the Urenco board himself in August 1971, presenting it as a paper prepared at the request of the Urenco Organization Working Group.[64] After the paper had been introduced to Urenco, Hughes then shared it with the UKFCO on an unclassified basis.[65] By early September 1971, Parry's paper had been adopted as Urenco's formal position on GCEP safeguards.[66]

Now Urenco's official position, Parry's draft would become known as the 'Parry Paper.' The paper would not become the official position of the Troika governments, however, until March 1972,

[62] Parry sent his paper to Morgan and Hughes for comments on July 6, 1971. See J.V.L. Parry to F. Morgan and H. Hughes, "Draft on URENCO Safeguards Papers" (July 6, 1971), attachment to F. Morgan to M.J. Newington, SSCD/71/166, TNA FCO 55/760/55 (July 27, 1971).
[63] F. Morgan to M.J. Newington, SSCD/71/166, TNA FCO 55/760/55 (July 27, 1971).
[64] J.V.L. Parry to H.E. Schimmelbusch et al. (August 3, 1971), attachment to H.A. Hughes to M.J. Newington, "Safeguarding of Centrifuge Plants," TNA FCO 55/760/65 (August 16, 1971).
[65] H.A. Hughes to M.J. Newington, "Safeguarding of Centrifuge Plants," TNA FCO 55/760/65 (August 16, 1971).
[66] D.G. Avery to P.J. Kelly, "Safeguarding of Centrifuge Plants," TNA FCO 55/760/70 (September 2, 1971).

when it was approved by the JC in preparation for talks with the United States, as well as for the June 1972 IAEA Technical Working Group.[67] At the same meeting, a decision was also taken to transmit the Parry Paper to Euratom, to follow up on correspondence received earlier that month.[68] In this way, what had been essentially a British position on enrichment safeguards became the agreed position of the tripartite governments, with seemingly little resistance or input from the FRG or the Netherlands. An exchange of letters between the UKFCO and the FRG Ministry of Education and Science (BMBW) indicates that the FRG government carried no objections to the Parry Paper, although a German safeguards expert, Professor Häfele, had mentioned that the Parry Paper could have highlighted possible containment measures more than it did in its current form,[69] (indeed, all versions of the Parry Paper, as circulated, do not prescribe nor discuss containment and surveillance measures for flows into or out of the process MBA). Häfele, however, did not have any fundamental concerns about the document.[70] Meanwhile, the Dutch seem to have been remarkably pliant over the course of the formation of the tripartite position. In informing the UKFCO of the Netherlands' assent to quadripartite talks with the United States, a Dutch embassy official made no comments on his country's preferred position on the matter.[71] There is no evidence indicating that the Dutch government made any substantial objections to content in the Parry Paper, prior to any engagement with the United States or the inspectorates.

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[67] Tripartite Joint Committee, "Minutes of tripartite meeting on classification and safeguards gascentrifuge-project held in the Hague at the Ministry of Foreign Affairs on 29th March 1972," JC/Clsaf/72/1, PA AA B 72 (ZA)/105295 (April 6, 1972), 2-3.
[68] Ibid., 3-4.
[69] A.W. Plattenteich to Sophia Lambert, ""Safeguarding" bei Urananreicherungsanlagen," BArch, B 196/10391 (January 11, 1972); Sophia Lambert to William Marsden, "Centrifuge Safeguards," TNA FCO 55/962/16 (January 25, 1972); Willam Marsden to Sophia Lambert, "Centrifuge Safeguards," TNA FCO 55/962/23 (February 8, 1972).
[70] A.W. Plattenteich to Sophia Lambert, ""Safeguarding" bei Urananreicherungsanlagen," BArch, B 196/10391 (January 11, 1972), 1.
[71] M.J. Newington to P.J. Kelly, "Quadripartite Talks with the Americans about Centrifuge Classification and Safeguards," TNA FCO 55/963/36 (March 7, 1972).

Over the course of the early 1970s, however, this initially unified Troika position would face strain and resistance—both internally, as a result of a Dutch decision to grant access to the cascade halls at Almelo in late 1973, and externally, as the Troika States struggled to find sufficient common ground with the United States. The latter disagreement between the Americans and Europeans, along with the IAEA's lack of internal expertise on GCEP technology, was instrumental in the IAEA's failure to adopt a coherent position on GCEP safeguards.

The IAEA Position

As efforts to create a GCEP safeguards approach began in the early 1970s, the IAEA chose not to proceed independently in the formation of its position. Although internal work was underway in mid-1971 to produce an IAEA paper on enrichment safeguards, the IAEA chose to approach experts from its Member States to contribute to the report, first consulting Dutch and German experts,[72] with the intention of engaging with American, British, and Soviet experts shortly thereafter.[73] When the IAEA informed the UK of its strategy, the UK Government became sensitive to IAEA cooperation with other States on enrichment safeguards, particularly with the United States. In July 1971 about one month after learning of the IAEA's intentions, the UKFCO learned that an American "technical team," including national laboratory personnel, had had discussions on safeguards in Vienna, and explicitly asked Freddy Jackson, UK Resident Representative to the IAEA, to investigate whether GCEP safeguards had been discussed.[74]

[72] UK Embassy Vienna to FCO, Telegram No. 320, TNA FCO 55/760/53 (July 26, 1971).
[73] UK Embassy Vienna to FCO, Telegram No. 233, TNA FCO 55/760/34 (June 11, 1971).
[74] UK FCO to Embassy Vienna, Telegram No. 195, TNA FCO 55/760/48 (July 21, 1971).

Although the IAEA provided no definitive evidence indicating that this was the case,[75] Jackson discovered in early August 1971 that American visitors had passed papers on gaseous diffusion to the IAEA Department of Safeguards, and that the current draft of the IAEA's safeguards paper, which covered both gaseous diffusion and gas centrifuge enrichment, had been passed to the United States.[76]

Perhaps without mere coincidence, aspects of the IAEA draft, as it existed at the time, shared much in common with the American position on enrichment safeguards. Most notably, the IAEA supported exceeding the lower MRIE provisions in INFCIRC/153 paragraph 80(c), in plants producing LEU enriched to less than 5%. The IAEA's position was made emphatically:

> "The MRIE in case of nominal enrichment up to 5% in about 100-120 man-days/year for a 100 tons SWU plant and 200-300 man-days for a 1000 tons SWU plant. **These values are definitely too low for the implementation of effective safeguards** [emphasis added]. They do not give the possibility, even in case of a relatively large plant, for an inspection regime assuring the continuity of knowledge concerning the flow of material and the effective control of containment. The continuity of observation is an important requirement especially in those types of plants where a re-arrangement of the cascade or the recycling of the enriched product may occur and consequently there is the possibility of using a portion of separative power for production of highly enriched U. Therefore the 100 + 0.4

[75] Rudolf Rometsch, the IAEA Inspector General, confirmed to UK representatives in late July that the IAEA had consulted with a Dutch national (Barendregt) and an FRG national (Zippe), as mentioned in the previous chapter. No mention is made of talks with the United States in the UK account of this conversation. See UK Embassy Vienna to FCO, Telegram No. 320, TNA FCO 55/760/53 (July 26, 1971).
[76] F.H. Jackson to M.J. Newington, "Safeguards on Enrichment Plants," TNA FCO 55/760/60 (August 4, 1971).

E formula[77] can be applied only in such cases where it can be verified that the facility is not suitable for production of material with more than 5%-enrichment."[78]

Clearly, the IAEA's assessment of the ease with which a centrifuge plant could be reconfigured conflicted with that of the Troika. Furthermore, with this language, it could be construed that the IAEA supported contravening the language of the model safeguards agreement that had been approved by the Board of Governors only months beforehand, after painstaking multilateral negotiations. Although the last sentence of the paragraph states that the lower MRIE limit could be applied at facilities "not suitable" for producing 5%-enriched material or greater, there is no mention about how this determination could be made. The mention of "continuity of observation" bears resemblance to the American perimeter safeguards concept, with its constantly manned portals, although the IAEA draft paper makes no mention of that approach. The IAEA draft, however, did recognize the idea of restricting inspector access, in line with the American and European positions, in this case calling for two MBAs in an enrichment plant, an 'open' MBA for feed preparation and blending areas (presumably including the withdrawal cells as well) and a 'closed' MBA containing the cascade area.[79]

Of course, the Europeans took no issue with the IAEA's position on cascade access. However, the IAEA's position on MRIE was totally incompatible with the Troika approach, and in particular the positions of the UK and the FRG. Within a week of receiving the paper from the IAEA, the

[77] This refers to the lower MRIE Limit in INFCIRC/153, para. 80(c).
[78] International Atomic Energy Agency, "Safeguards in Enrichment Plants (First Report)" (1971), 17, attachment to F.H. Jackson to M.J. Newington, "Safeguards on Enrichment Plants," TNA FCO 55/760/60 (August 4, 1971).
[79] Ibid., 7.

UKFCO made a note of the draft's comment on insufficient MRIE, and passed the paper on to Frank Morgan, who argued that the UK should make a stronger case that GCEPs were less flexible than appear.[80] The UK Department of Trade and Industry (DTI) noted, however, that the IAEA's paper was "quite a good bit of work, considering that so little has been published about enrichment plants; and we have so far not helped them by providing expert advice,"[81] thus implicitly noting the possibility that the IAEA's statement on MRIE may have been based on incomplete information, instead of upon American influence. By December 1971, the UK Government resolved to send Morgan and Hughes to speak with IAEA safeguards officials about the paper, in the same way that the UK had perceived that the Americans had done, without actually revealing the actual British position on GCEP safeguards.[82]

The meeting between Morgan, Hughes, and the IAEA served the UK's interests well. Upon speaking with the IAEA in late January 1972, Morgan and Hughes gained the impression that the IAEA's position on MRIE had not been implanted by the United States – instead, U.S. representatives had apparently visited the IAEA in December 1971 to push the IAEA to strengthen its position on the issue, while the IAEA was merely "ill-informed."[83] A U.S. State Department cable indicates that Herbert Kouts, an employee of Brookhaven National Laboratory who would soon take a key role in quadripartite interactions over GCEP safeguards, was sent to meet with the

[80] M.J. Newington to F. Morgan, "Safeguards on Enrichment Plants," TNA FCO 55/760/61 (August 10, 1971); F. Morgan to M.J. Newington, TNA FCO 55/760/64 (August 13, 1971).
[81] P.J. Kelly to F.H. Jackson, "Safeguards on Enrichment Plants," TNA FCO 55/761/108 (December 23, 1971), 1.
[82] Ibid.
[83] F. Morgan to H.A. Hughes, "Note for the Record," SSCD/72/24, TNA FCO 55/962/20 (January 31, 1972), 1.

IAEA on December 6-7, 1971.[84] Clearly, it arose from the conversation that the United States was actively trying to influence the IAEA's position on the issue, as the IAEA itself was trying to gain expertise on GCEP technology. IAEA officials revealed to Morgan and Hughes that Kouts, relative to others in the U.S. safeguards community, took a particularly hard line on the issues that the Troika found objectionable, but that other voices, including Oak Ridge National Laboratory and ACDA, were more sympathetic to the Troika view, reflecting the internal discord on GCEP safeguards within the U.S. government. As a result of the meeting, the IAEA agreed to revise "bold statements unsupported either by reasoning or facts" (from the UK perspective) to instead be posed as unanswered questions.[85] The final version of the IAEA's position paper, published in October 1972 as a Safeguards Technical Report No. 14 (STR-14) is very vague about MRIE at enrichment facilities, making no judgment as to whether the INFCIRC/153 limits were sufficient, or on how to resolve the question of whether to apply INFCIRC/153 paragraph 80(b) or 80(c). Instead of the highly definitive language on MRIE in the draft quoted earlier, the published version of STR-14 states:

> "Further studies are needed to determine whether the use of isotopic mass balance data and other objective methods or instruments can be applied intermittent basis within MRIE. In addition, it is necessary to take into account the dynamics of individual plants beofer [sic.] arriving at the correct conclusions.

[84] U.S. Department of State, State 206645, RG 59, *Subject-Numeric Files, 1970-1973*, Box 2865, AE 13: IAEA 6/1/71 (November 12, 1971). See also U.S. Mission to the IAEA, IAEA Vienna 7054, RG 59, *Subject-Numeric Files, 1970-1973*, Box 2865, AE 13: IAEA 6/1/71 (November 5, 1971).
[85] F. Morgan to H.A. Hughes, "Note for the Record," SSCD/72/24, TNA FCO 55/962/20 (January 31, 1972), 1.

> For plants operating with a product concentration greater than 5% U-235, the MRIE would allow daily coverage, if necessary; continuous coverage depends on the size of the plant and nominal enrichment."[86]

Shortly after Morgan and Hughes' IAEA visit, the UK informed the FRG government that the meeting had taken place. An FRG Foreign Office (Auswärtiges Amt, AA) memo notes that West German safeguards experts had identified the same issues with the IAEA paper as had the British safeguards community, upon receiving the IAEA paper on a confidential basis.[87] However, the FRG Government had decided not to engage the IAEA at the time, and instead planned to withhold its concerns until the June 1972 Technical Working Group.[88] The U.S. Government also learned about the meeting through an IAEA staff member who met with Morgan and Hughes. A U.S. cable summarizing the meeting[89] indicates that the IAEA perceived the UK's dissenting position to be very strong. Reportedly, British experts made argued ardently against the use of containment and surveillance (C/S) to compensate for access limitations, and that Morgan and Hughes presented "persuasive data" to argue that safeguards at fuel fabrication plants actually required more effort than safeguards at enrichment plants.[90]

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[86] Istvan Kiss, *Safeguards in Enrichment Plants*, STR-14 (Vienna: International Atomic Energy Agency, October 1972), 15.
[87] Randermann, "Sicherheitskontrollen bei Anreicherungsanlagen; Britische Reaktion auf das sog. Kiss-Papier der IAEO," PA AA, B 72 (ZA)/105295 (February 7, 1972).
[88] Ibid.
[89] U.S. Mission to the IAEA, IAEA Vienna 658, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 24, IAEA 8-4: Technical Wrkg Grp, Safeguards Procedures for Isotopic Enrichment Facilities, 1972 (February 2, 1972).
[90] Ibid., 2.

The IAEA's lack of expertise on GCEP safeguards led the organization to being highly deferential towards its Member States for information. Because Member State GCEP safeguards concepts were incompatible with each other, however, the IAEA was essentially unable to support any particular safeguards approach or specific position on controversial issues, for fear of unfairly supporting one State's ideas over another's. By contrast, Euratom was similarly ill equipped to evaluate GCEP technology, but took a far less consultative – and a far more confrontational – stand against its Member States. The next section analyzes the dynamics that contributed to Euratom's position.

The Euratom Position

Like the IAEA in the early 1970s, Euratom was also not endowed with technical knowledge on the gas centrifuge enrichment process. Despite the decision of the United States to project confidence in Euratom safeguards immediately following signature of the Treaty of Almelo, in reality, no specific measures for Euratom GCEP safeguards had been agreed upon at the time. In October 1970, the U.S. State Department queried the U.S. Embassy in Brussels as to the "precise character" of the Euratom safeguards to be applied at Almelo.[91] The embassy replied that although a staff study been initiated on Almelo safeguards in the summer of 1970, work had been delayed as a key staff member had instead been occupied with the safeguards approach for the EUREX reprocessing plant.[92] Franco Cancellario d'Alena, at the time Director-General of the Euratom Commission's Supply Agency and Security Office, reported to American officials, "there is

[91] U.S. Department of State, State 168752, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 17, SCI 10: FRG/UK/Dutch Centrifuge Cooperation, 1970 (October 13, 1970).
[92] U.S. Embassy Brussels, EC Brussels 4633, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 17, SCI 10: FRG/UK/Dutch Centrifuge Cooperation, 1970 (October 19, 1970), 1.

nothing that can be said at this point about the precise character of the safeguards to be applied at Almelo."[93] Brussels also reported that Euratom's response to questions in the past on safeguards at Almelo did not go much further beyond the mere statement that Euratom safeguards would be applied to Almelo, in adherence to Dutch and German commitments.[94] Later correspondence between Euratom, Uranit, and the BMBW suggests that the earliest work was indeed superficial in nature. Work towards a safeguards approach for the German pilot plant was initiated in July 1970 following a notification by Uranit to Euratom pursuant to Article 41 of the Euratom Treaty.[95] This provision, however, merely requires persons and enterprises involved in nuclear fuel cycle activities to report any new investment projects to the Euratom Commission (EC),[96] not primarily in the context of safeguards, but in order to improve coordination of investment projects across Euratom Member States. While Euratom apparently responded to this notification nearly one year later, in July 1971, substantive discussion of safeguards measures between the inspectorate and operators did not begin in earnest until March 1972, when Fernand Spaak, Director General for Energy and Euratom Safeguards in the Commission of the European Communities, informed UCN and Uranit of Euratom's intentions for initial Euratom safeguards activities at Almelo.[97]

Before describing Euratom's attitude to GCEP safeguards further, it is worth briefly reiterating that the legal framework for Euratom safeguards activities differs substantially from that of the

[93] Ibid.
[94] Ibid.
[95] Fernand Spaak, "Anwendung der Sicherheitsüberwachung nach Kapitel VII des Euratom-Vertrages in der von Ihnen zu errichtenden Anlage zur Herstellung angereicherten Urans durch das Gaszentrifugenverfahren in ALMELO/Niederlande," BArch B 196/10896 (March 2, 1972).
[96] "Treaty establishing the European Atomic Energy Community (Euratom)," art. 41.
[97] Fernand Spaak, "Anwendung der Sicherheitsüberwachung nach Kapitel VII des Euratom-Vertrages in der von Ihnen zu errichtenden Anlage zur Herstellung angereicherten Urans durch das Gaszentrifugenverfahren in ALMELO/Niederlande," BArch B 196/10896 (March 2, 1972); "Aide-Memoire No. 4288-580," TNA FCO 55/963/39 (March 15, 1972).

IAEA's safeguards regime. Most importantly, in essence, the legal basis for Euratom safeguards in the early 1970s derived solely from Articles 77-85 of the Euratom Treaty. Unlike the IAEA's comprehensive safeguards system, Euratom safeguards practices were not elaborated further by a legal document akin to INFCIRC/153 for operationalizing the obligations of the State and inspectorate under the Treaty. Apart from two short protocols, Regulation No. 7 (also referenced elsewhere as Regulation No. 2)[98] and Regulation No. 8,[99] which respectively detailed procedures for reporting facility design information and material accounting records, no other agreed documents existed for governing the implementation of Euratom safeguards, apart from the Treaty itself. Thus, in general, there existed more room for interpreting the safeguards-related rights and responsibilities of both Euratom and its Member States. No provision existed in the legal basis for Euratom safeguards allowing the restriction of inspector access, as access must be granted "to the extent necessary in order to apply such safeguards to ores, source materials and special fissile materials and to ensure compliance with the provisions of Article 77."[100] No language exists in the Euratom Treaty or in Regulations 7 and 8 on limits for inspection effort, or on any special measures

[98] There exists some confusion over the number designation of this Euratom regulation, which governed the procedure for declaring design information for new facilities pursuant to Article 78 of the Euratom Treaty. Contemporary documents from the early 1970s refer to this document as Regulation No. 7. See Spaak, "Anwendung der Sicherheitsüberwachung…," BArch B 196/10896 (March 2, 1972); Stieff Research and Development Co., Inc., "Euratom and Regional Safeguards," Appendix IX-D in *Nuclear Proliferation and Safeguards Appendix Volume II Part Two,* (Washington: U.S. Office of Technology Assessment, 1977), IX-80. However, this document is listed under the EU's official EUR-Lex portal for EU law as Regulation No. 2 of the European Atomic Energy Community (see *Official Journal of the European Union* 15 (March 12, 1959): 298/59, http://data.europa.eu/eli/reg/1959/2/oj). To add to this confusion, the English version of the regulation in the *Official Journal* is titled as Regulation No. 2, although the annex to the document (contained in the same electronic file) is titled as an "Annex to Commission Regulation No 7." Meanwhile, the Italian version of the same document was originally titled as Regulation No 2 in the electronic document available through EUR-Lex, but the number "2" is crossed out and replaced with a handwritten "7." Thus, it seems that the document was originally designated as Regulation No. 2 and renumbered, possibly informally, as Regulation No. 7 at a later date. In this dissertation, the regulation will be referred to as Regulation No. 7.

[99] *Official Journal of the European Union* 34 (May 29, 1959): 651/59, http://data.europa.eu/eli/reg/1959/8/oj.

[100] "Treaty establishing the European Atomic Energy Community (Euratom)," art. 81.

to be undertaken due to limits to inspector access (as the latter issue is precluded by the inability of Euratom inspector access to be limited in the first place). Thus, under the context of Euratom safeguards implementation, there was no space for a debate to take place over the issue of inspection effort, as was taking place between the United States and the Troika over IAEA safeguards. However, the lack of concrete guidance over what types of inspector access were deemed to be 'necessary' under Euratom safeguards created an atmosphere primed for conflict, given the sensitivity with which GCEP technology was treated at the time. The issue of inspector access to sensitive areas of GCEPs, particularly cascade halls, was indeed the central issue in the dispute between Euratom and the Troika over safeguards implementation at GCEPs, with Euratom taking a pro-access stance, and the Troika States making efforts to resist access. The bravado with which Euratom pursued its case against its own Member States, however, in contrast with the IAEA's consultative approach, is also remarkable. Unlike the IAEA, Euratom pursued an ability to verify the absence of facility misuse, including HEU production, from the very beginning. This strategy, however, led to political confrontation with Troika States.

In pursuing an agreement on safeguards measures for Almelo, Euratom, led by Spaak, was remarkably aggressive. In the version of the March 1972 letter dispatched to Uranit, noting the special characteristics ("besondere Merkmale") of the enrichment facility, Spaak announced Euratom's intention to carry out a design verification inspection, as well as to evaluate operating procedures at the facility with the implication that they would either be approved or disapproved by Euratom ("ein Verfahren zur Zustimmung der in Ihrer Anlage angewandten

Betriebsverfahren").[101] The first phase of this work, according to Spaak, would entail checking whether building plans, chemical and physical processes to be used, equipment, and qualitative and quantitative safeguards measurement protocols would be permissible ("zulässig") to Euratom.[102] Following this evaluation, Euratom would give a definitive approval on whether construction activities matched building plans, and whether operating procedures were appropriate for the implementation of safeguards.[103] This language seems to have disturbed a BMBW official, who underlined the word "zulässig" and marked it with a large question mark in the copy of Spaak's letter to Uranit that was dispatched to his organization. Upon completion of the facility, Euratom would again check whether the approved building plans matched the finished facility, as well as whether the material accountancy procedures were satisfactory. In a third phase, Euratom would conduct another evaluation and approval once the facility was undergoing cold testing.[104] In closing, Spaak argued that safeguards measures for enrichment plants should be developed collaboratively between inspectorates and operators, based upon theoretical considerations and practical experience, in a similar approach to that which had been carried out at reprocessing facilities, proposing bilateral talks between Germany and Euratom in the near future.[105] This reference to reprocessing facilities carried special weight, as Article 78 of the Euratom Treaty requires procedures used in chemical reprocessing to be approved by the EC.[106] Although the Euratom Treaty does not explicitly give the EC power to approve enrichment procedures, Spaak was arguing that given the similarities in nature of enrichment and reprocessing (both being used

[101] Fernand Spaak, "Anwendung der Sicherheitsüberwachung nach Kapitel VII des Euratom-Vertrages in der von Ihnen zu errichtenden Anlage zur Herstellung angereicherten Urans durch das Gaszentrifugenverfahren in ALMELO/Niederlande," BArch B 196/10896 (March 2, 1972), 1.
[102] Ibid., 2.
[103] Ibid.
[104] Ibid.
[105] Ibid., 3.
[106] "Treaty establishing the European Atomic Energy Community (Euratom)," art. 78, para. 2.

in production of fissionable material), Euratom authority to approve reprocessing safeguards processes could also apply to those in enrichment plants. In addition, Euratom's access request was bold, in the face of contemporary classification rules covering centrifuge and cascade equipment.

This legal bravado was accompanied by action on the part of Euratom. On March 14, 1972, less than two weeks after Spaak's letter was dispatched, two Euratom inspectors visited at the Dutch pilot plant at Almelo, which was under construction at the time. The inspectors were tasked with examining technical details of the facility, under Regulation No. 7. During this visit, the plant manager barred them from accessing the cascade area and from inspecting the plant's control panel.[107] This inspection was the first in a series of visits, during which Urenco (reportedly under direction of the Dutch government)[108] prevented Euratom inspectors from accessing sensitive parts of the Almelo pilot facilities. The decision to restrict the access of Euratom inspectors at Almelo, however, was questionable from a legal standpoint, contingent upon the necessity of the access, under Article 81 of the Euratom Treaty.

Spaak's letter was discussed at a Troika Joint Committee meeting on March 29, 1972. At this meeting, the FRG delegation explicitly voiced its disapproval of Spaak's argument for giving Euratom the authority to approve operational procedures at Almelo.[109] An FRG representative expressed dismay at the lack of legal basis for Euratom's suggested approval process, upon sharing

[107] F. Spaak to Prof. Bogaerdt, translated from Dutch into German, 105(ZA5)-2715/72, BArch, B 196/10391 (July 28, 1972), 2.
[108] Ibid., 3.
[109] Tripartite Joint Committee, "Minutes of tripartite meeting on classification and safeguards gas centrifuge-project held in the Hague at the Ministry of Foreign Affairs on 29th March 1972," JC/Clsaf/72/1, PA AA, B 72(ZA)/105295 (March 29, 1972).

the letter sent to Uranit.[110] Furthermore, the FRG delegate (as reported by the UKFCO) complained of the "impropriety" of Spaak's letter to Uranit, as it had also been sent to the wrong address.[111] The JC decided to rebuff Spaak's invitations for bilateral consultations between Euratom and individual technology holders, instead suggesting a meeting with Euratom, in which the Troika governments would seek to bring Euratom's approach into line with their own policy on the matter. The Troika, in responding to Spaak's March 2 letter, transmitted the Parry Paper to Euratom, along with a diplomatically phrased letter signed by Bob Wansink, who chaired the JC during 1972. The letter did not go far beyond merely introducing the Parry Paper, along with an invitation for Euratom to meet with the Troika on May 17, 1972.[112] Official responses made separately by the Dutch and German governments to Spaak's letter, however, reflected the starker disagreement. The German response argued that Euratom had no authority to declare whether certain measures were "permissible" at an enrichment plant,[113] while the Netherlands declared that it "does not wish to commit itself" to Euratom's proposal to approve of processes used at Almelo.[114] In return, Euratom reportedly took issue with references in the Parry Paper to protection of sensitive information, as the Euratom Treaty did not provide for inspector access limits on the basis of the protection of classified data, leading the Troika to send Euratom another revised version, this time with all references to the protection of sensitive information removed.[115] The new version of the

[110] N.M. Fenn to S.J. Lambert, "Centrifuge Safeguards," TNA FCO 55/963/60 (April 4, 1972).
[111] Ibid.
[112] Letter from L.G. Wansink to F. Spaak, JC/SEC/72/7, BArch, B 196/10896 (April 10, 1972).
[113] Plattenteich to F. Spaak, IC2 – 9555 – 1/72, BArch, B 196/10896 (March 27, 1972).
[114] L.M.J. van de Winkel to Euratom Commission, translated from Dutch into English, BArch, B 196/10896 (April 26, 1972).
[115] U.S. Mission to the IAEA, IAEA Vienna 8720, RG 59, *Subject-Numeric Files, 1970-1973*, Box 2863, AE 13: EURATOM 6/1/72 (December 14, 1972), 2; N.M. Fenn to J.L.K. Thompson, "Centrifuge Safeguards," TNA FCO 55/964/103 (May 19, 1972).

Parry Paper argued solely that cascade hall access was unnecessary for effective Euratom safeguards.[116]

By the summer of 1972, Euratom had relented on the issue of approving operational procedures at Almelo but doubled down on cascade access at the facility. Although a consultation between Euratom and UCN had taken place on April 28, 1972, as had the planned Troika-Euratom meeting on May 17, 1972, a July 1972 letter from Spaak to UCN reflected a stark disagreement on the access question.[117] In this letter, Spaak brought up the initial design verification visit to Almelo that had taken place in March, and argued that because the inspectors were unable to view the cascade area and centrifuge controls, they were unable to completely fulfill their assigned task.[118] Spaak then invoked Article 81 of the Euratom Treaty, arguing his experts had determined that without access to the cascade hall, effective safeguards would be nearly impossible.[119] Cascade hall access would be required for verifying actual enrichment levels at the plant, verifying the absence of undeclared enrichment capacity, verification of maximum attainable enrichment levels in cascades under possible configurations, and verification of the absence of undeclared feed and takeoff lines.[120] Thus, the tacit assumption underlying Spaak's argument, which conflicted directly with Parry's safeguards concept, was that Euratom safeguards should verify the non-misuse of a GCEP, and not just verify non-diversion by conducting material balance calculations on incoming

[116] U.S. Mission to the IAEA, IAEA Vienna 8720 (December 14, 1972), 2.
[117] F. Spaak to Prof. Bogaerdt, translated from Dutch into German, 105(ZA5)-2715/72, BArch, B 196/10391 (July 28, 1972).
[118] Ibid., 3.
[119] Original German: "Meine Sachverständigen… sind zu dem Ergebnis gelangt, dass… eine wirksame Überwachung ohne Zugang der Zentrifugenhalle kaum zu verwirklichen ist." Translation: "My experts… have concluded that… a workable verification without access to the cascade halls is unlikely to be realized." Ibid., 4.
[120] Ibid.

and outgoing material. The need for cascade hall access followed from the former goal, i.e. cascade hall access was primarily useful for verifying that the absence of facility misuse via excess enrichment or undeclared material. Nevertheless, access to the cascade hall could provide confidence in non-diversion as well, in that any products of facility misuse would likely be diverted from reported stocks.

The Situation before the June 1972 IAEA Technical Working Group

By the time the IAEA Technical Working Group on Enrichment Safeguards met in June 1972, differences in policy between the United States, the Troika, the IAEA and Euratom were apparent to all parties involved, making GCEP safeguards even more sensitive and complicated than when all parties were making efforts to avoid engagement on the issue. Exchanges between the UK and United States over GDP safeguards, as well as bilateral interactions between the two countries and the IAEA, had revealed transatlantic differences in interpretation of key parts of INFCIRC/153. As a result of this conflict, and the IAEA's deference to Member State advice, the IAEA's position on GCEP safeguards became subject to an ongoing tug of war match between the UK and United States. Meanwhile, Euratom, faced with less conflict than the IAEA experienced among its Member States, began to lock horns with its own Member States over the issue of cascade hall access.

It is curious why the IAEA and Euratom took such different approaches in interacting with stakeholder States over GCEP safeguards, given that both organizations were equipped with minimal technical expertise for tackling the issue. This question could be answered by dynamics

observable at low and high policymaking levels. At a lower level, the dichotomy could be partially explained by different personalities of the leadership at the IAEA and Euratom. Correspondence from Euratom to UCN, Uranit, and the Dutch and West German governments made Euratom's intentions on cascade access perfectly clear, without displaying much empathy at all for the positions of the Member States. Although some briefs, such as the March 3, 1972 letters, are known to have been drafted by lower level staff (in this case, an inspector named E. van der Stijl, who would also participate in Euratom inspections at Almelo),[121] DG Spaak's approval and signature of these letters imply that Euratom's confrontational approach was at least accepted under his leadership. An official at the UK Department of Trade and Industry, Peter Kelly, made note of the 'self-importance' of the Euratom Commission, shortly after the UK Government learned of Euratom's March 1972 overture.[122] On the other hand, the IAEA's safeguards leadership – in particular, Inspector General (IG) Rudolf Rometsch – was heavily criticized from within the organization as being unacceptably weak in negotiating safeguards measures with Member States. Some IAEA safeguards staff, most notably Slobodan Nakićenović, Director of the IAEA's sole Division of Operations at the time,[123] perceived that Rometsch was folding against the desires of Member States, to the detriment of effective verification as the IAEA began its work to implement comprehensive safeguards. In July 1976, Nakićenović penned a strongly worded 8-page memorandum to Rometsch, in which he compiled all of his complaints against Rometsch that had amassed since Nakićenović took up his position in 1970. To highlight the extent of Nakićenović's frustration, he wrote:

[121] N.M. Fenn to S.J. Lambert, "Centrifuge Safeguards," TNA FCO 55/963/60 (April 4, 1972).
[122] P.J. Kelly to N.M. Fenn, "Safeguards for Almelo Enrichment Plant: Contacts with the Commission," CW/138/028, TNA FCO 55/963 (March 16, 1972).
[123] This position lies immediately below the IAEA Inspector General (who is now known as the Deputy Director General for Safeguards). The Safeguards Operations Directorate (of which there are three today), housed the IAEA's staff of inspectors.

> "I can best summarize my views of the situation in my Division since 1970 by saying that it appears to me that many of the major initiatives you have taken have had an adverse effect upon safeguards, many initiatives you should have taken to improve safeguards you did not take, and many initiatives which you stifled would have benefitted safeguards."[124]

Nakićenović was particularly concerned by Rometsch's initiative to reduce IAEA inspection effort as a tradeoff for more effort by State safeguards authorities, particularly in Euratom States and in Japan, by implementing the concept of Average Routine Inspection Effort (ARIE) to which the IAEA would adhere.[125] ARIE would necessarily be lower than the MRIE defined in INFCIRC/153. To attain a lower amount of inspection effort while maintaining safeguards effectiveness, Rometsch had endorsed use of the 'black box' concept,[126] in line with the wishes of the European GCEP technology holders. Nakićenović, however, feared that the use of non-access areas could become a liability to effective safeguards, for example, if seals around an area off-limits to inspectors were to fail.[127] Had Nakićenović been in Rometsch's position at the time, it is certainly possible that the IAEA might have stood up more aggressively to Member State pressure.

Political pressure at higher levels could also explain the differences between IAEA and Euratom. In the early 1970s, Euratom's safeguards role was the subject of intense debate as negotiations

[124] Slobodan Nakićenović to Rudolf Rometsch, "Instructions and Guidelines Regarding Organization of Safeguards Work," Interoffice Memorandum, International Atomic Energy Agency, PA AA, B 72 (ZA)/119530 (July 30, 1976), 8.
[125] Ibid., 3.
[126] Nakićenović's complaint was made specifically in the context of using the black box concept to verify fuel assemblies, but Rometsch's acceptance of the non-access concept was of course highly relevant to inspector access regimes for sensitive areas of GCEPs.
[127] Ibid., 3.

towards an IAEA-Euratom safeguards agreement began. Clearly, Euratom had no interest in having its verification function subsumed entirely by IAEA comprehensive safeguards activities. This, in addition, would run counter to Article 77(b) of the Euratom Treaty, which requires that the Euratom Commission satisfy itself of Member States' adherence to any "special undertaking concerning measures of control entered into by the Community in an agreement concluded with a third country or an international organization."[128] If cascade hall access for IAEA inspectors were to be restricted under INFCIRC/153 paragraph 46(b)(iv), the then-unique ability of Euratom inspectors to access GCEP cascade halls would have increased the relative importance of Euratom activities under NPT safeguards, thus increasing the institution's relevance. Also, at a higher level, Euratom did not face two groups of opposing stakeholders as the IAEA did, and thus did not have to avoid the appearance of favoring one group's position over another. If the IAEA had taken a firm position on MRIE, then either the United States or the Troika could have accused the IAEA of unwarranted favoritism towards the opposing side. This argument would have been strengthened by the fact that the IAEA did not have particularly strong expertise on which to base this decision, and thus the perception would be that the IAEA's decision was solely politically motivated. On the other hand, Euratom, although still lacking in expertise, could advance its case against the Troika without being accused of being motivated by the United States, or perhaps the Soviet Union.

[128] "Treaty establishing the European Atomic Energy Community (Euratom)," art. 77(b).

The June 1972 IAEA Technical Working Group: Ceasefire

In addition to the reasons given in the previous section, the IAEA may not have taken a firmer position because the United States and Troika also made efforts to appear closer to agreement on GCEP safeguards than they actually were, in particular, during the run-up to the June 1972 Technical Working Group. Records from preparatory quadripartite meetings indicate that disagreements were indeed stark. At the first quadripartite talks, held at the USAEC Headquarters near Washington, DC on April 19-20, 1972, opposing viewpoints were put on full display. The United States, although it had not yet adopted a concrete position on its favored degree of inspector access, did articulate its interest in perimeter safeguards, along with its estimates for routine inspection effort. Delegates from the Troika duly noted that these levels (shown in Table 4-2) exceeded the MRIE given in INFCIRC/153 paragraph 80(c) by about a factor of forty.[129,130] A British account of the meeting reports that the German delegation subsequently became "indignant," and "spoke privately of protesting to the Americans at a "high political level.""[131] Minutes from the meeting compiled by the USAEC reflect a similar reaction to the U.S. position, reporting, "it was asserted that the IAEA could not apply "police measures" to centrifuge plants," referencing surveillance measures being applied to personnel and packages entering and exiting the plant.[132] A German report transmitted after the meeting was most critical, criticizing the U.S. concept as a case of 'evangelistic perfectionism' ("missionarisch-perfektionistische Safeguards-

[129] Wegener, "Besprechungen mit der amerikanischen Regierung über das Ausmaß von Sicherheitskontrollen bei Gasultrazentrifugenanlagen," Meeting record (Aufzeichnung), BArch, B 196/10391 (April 28, 1972).
[130] UK FCO to Embassy Washington, Saving Telegram No. 4, TNA FCO 55/964/81 (April 24, 1972).
[131] Ibid.
[132] U.S. Atomic Energy Commission, "Summary of the Washington Meeting on Safeguards in Gas Centrifuge Plants, U.S.-Tripartite Centrifuge Consortium, April 19-20, 1972," 2, enclosure to Zook to van Vierssen, BArch, B 196/10391 (May 9, 1972).

Auffassung").[133] The German account also characterized the American plan as "completely absurd" with respect to the IAEA's staffing availability ("völlig absurde Relation zur personellen Leistungsfähigkeit der IAEO").[134] During the meeting, the United States tried to walk some of its arguments back, emphasizing that the U.S. position was not set in stone, and that it would be possible to set aside invocation of INFCIRC/153 paragraph 76(d) if the higher MRIE limits under paragraph 80(b) were upheld instead.[135] This step did not satisfy the Troika delegation. Furthermore, even the design information assumptions in the Parry Paper and U.S. paper were radically different: while the Parry Paper (as agreed by Urenco in 1971) estimated an inventory on the order of 100 milligrams for a single centrifuge,[136] the U.S. paper estimated an inventory 5-20 grams per machine.[137] Thus, while the Europeans argued that the gas phase inventory of a cascade was negligible for material balance purposes, the Americans argued that this inventory could be highly significant: in fact, 7.6 metric tons of uranium for a 3800 tSWU/a reference plant in the centrifuge rotors alone.[138] This would scale down to 50 kg of uranium for a 25 tSWU/a pilot facility. The USAEC minutes, in summing up the meeting, stated plainly, "[i]t was agreed that the U.S. and the Tripartite members do not have the desired degree of agreement-needed before the June IAEA Working Group on Safeguards Procedures for Isotope Separation Facilities."[139] On the first day of the meeting, both U.S. and Troika delegations agreed to prepare their own statements

[133] Wegener, "Besprechungen mit der amerikanischen Regierung über das Ausmaß von Sicherheitskontrollen bei Gasultrazentrifugenanlagen," Meeting record (Aufzeichnung), BArch, B 196/10391 (April 28, 1972), 3.
[134] Ibid.
[135] UK FCO to Embassy Washington, Saving Telegram No. 4, TNA FCO 55/964/81 (April 24, 1972), 2.
[136] Jack V.L. Parry, "The Safeguarding of Centrifuge Plants," EOB(71)18, PA AA, B 72 (ZA)/105295 (August 2, 1971), 1.
[137] U.S. Atomic Energy Commission, *An Analysis of Safeguards at Gas Centrifuge Plants*, TNA FCO 55/964 (March 24, 1972), 3.
[138] Ibid., 45.
[139] U.S. Atomic Energy Commission, "Summary of the Washington Meeting on Safeguards in Gas Centrifuge Plants, U.S.-Tripartite Centrifuge Consortium, April 19-20, 1972," 8.

summarizing positions that were voiced at the meeting. The Tripartite statement articulated the most hardline position voiced by the three States, essentially stating that the verification of GCEP misuse, contrary to the U.S. position,[140] was completely outside the purview of INFCIRC/153-type safeguards:

> "Safeguards are to be instituted for the exclusive purpose of verifying that nuclear material is not diverted. Safeguards measures may therefore only aim at the early discovery of actual diversion, and not at its prevention, nor at counteracting other modes of utilizing the plant."[141]

The first U.S.-Troika meeting on GCEP safeguards, thus, did not produce promising results. The two sides could not even agree on the very purpose of IAEA safeguards: while the United States sought to give the IAEA power to verify the absence of GCEP misuse, the Troika argued that such a situation was not credible.[142] In order to facilitate closer agreement prior to the IAEA Technical Working Group, the United States suggested discussing GCEP safeguards immediately following the quadripartite meeting on classification in The Hague that had already been planned for May 1972.[143] Given that U.S.-Troika thinking on centrifuge classification issues was generally harmonious, one might have thought that this spirit could have facilitated agreement on the

[140] The U.S. position on facility misuse, as written in the U.S. statement, was as follows: "The IAEA should have some means of providing independent assurance that highly enriched uranium is not being produced in a plant declared to be producing only low enriched uranium." See "U.S. Summary of Positions," 3, Appendix D in Ibid.
[141] "Statement of Tripartite Group," BArch, B 196/10391 (April 19, 1972).
[142] U.S. Atomic Energy Commission, "Summary of the Washington Meeting on Safeguards in Gas Centrifuge Plants, U.S.-Tripartite Centrifuge Consortium, April 19-20, 1972," 8, appendix D, 3.
[143] Donovan Zook to C.H. van Vierssen, BArch, B 196/10391 (May 9, 1972).

safeguards issue. In the meantime, the FRG backed down on its threats for high-level diplomatic action in the immediate future, to the relief of the UK government.[144]

The safeguards portion of the May 1972 quadripartite meeting, however, made very little headway. While agreement remained on the need to restrict inspector access, discord persisted on the question of verifying facility misuse, and on the acceptable intensity of inspections. Minutes from this meeting from the Troika delegation stated, "the positions of the two delegations had not moved any closer."[145] Nevertheless, the quadripartite group made a final attempt at closer agreement in Brussels on Friday, June 9, 1972,[146] directly before the IAEA working group. Both sides had an interest in avoiding open disagreement at the IAEA meeting. First, the episode between the UK and United States over the U.S.-FRG Karlsruhe meeting, which had taken place the previous summer, was likely on the minds of British officials. Another U.S.-UK spat over GCEP safeguards would be detrimental to transatlantic nuclear safeguards cooperation. While the U.S. position was genuinely not set in stone, the Troika also benefitted from giving the IAEA the impression that sufficient technical progress had not yet been made on developing safeguards measures to make any decisions on a GCEP safeguards approach, thus preventing the IAEA from immediately adopting or favoring any particular approach that was undesirable to the Troika. Meanwhile, both the U.S. and the Troika could encourage the IAEA to adopt other aspects that were acceptable to

[144] Sophia Lambert to Nick Fenn, "Washington Talks on Enrichment Safeguards," TNA FCO 55/964/88 (April 27, 1972).
[145] Tripartite Joint Committee, "Minutes of the quadripartite meeting on safeguarding of centrifuge enrichment plants," PA AA, B 72 (ZA)/114137 (May 25, 1972).
[146] UK Embassy The Hague to FCO, Telegram No. 165, TNA FCO 55/964/105 (May 25, 1972); U.S. Department of State, State 101258, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 21, AE 13: Meeting on Centrifuge Classification & Safeguards - The Hague, 1972 (June 8, 1972).

both parties, such as no cascade access, on a provisional basis, while other points of disagreement were being resolved.

In the run-up to the last-minute Brussels meeting, the Americans and Europeans made efforts, in some cases with reluctance, to tone down the positions that they would present at the IAEA Working Group. The United States made the first move, offering to reduce its estimates for inspection effort if the Troika deleted references to MRIE limits in INFCIRC/153 in the Parry Paper.[147] Alternatively, the United States offered to reduce its manpower estimates if the Parry Paper were edited to be specific to the Almelo GCEP.[148] The UK Government, however, was wary of the proposal. Nick Fenn, a UKFCO official, noted that the promised reductions in inspection effort would come from use of yet-to-be developed technology, writing in a letter to Freddy Jackson in Vienna:

> "One difficulty is that the "locks, seals and tamper-proof devices" of which the Americans speak are little more than twinkles in American eyes. They are not yet in production. We are told they will be expensive ($1 – 300,000 for a plant like Almelo). We are assured that they will work. But we have no technical knowledge of them and even the Americans have not yet got operational experience of them [sic.]. One of our thoughts is that we might ask the Americans at Vienna to invite the IAEA Inspectorate to see such devices in operation in the US. That should put the fear of God into them."[149]

[147] UK Embassy The Hague to FCO, Telegram No. 165, TNA FCO 55/964/105 (May 25, 1972), 2.
[148] Ibid.
[149] N.M. Fenn to F. Jackson, "Safeguarding of Enrichment Plants," TNA FCO 55/964/111 (June 5, 1972), 2.

Meanwhile, from a political perspective, Fenn recognized that the removal of references to INFCIRC/153 would be strongly opposed by the FRG[150] (which would consistently take the most literal interpretation of INFCIRC/153 in GCEP safeguards discussions through the 1980s), and would leave the United States with the opportunity to engage the IAEA without using INFCIRC/153 as a legal basis.[151] By this stage, the FRG had indeed taken a more deeply entrenched position that the UK on the purpose of comprehensive safeguards. The instructions issued to the German representative to the IAEA Working Group explicitly called for making an effort to avoid any departures from activities supported by INFCIRC/153 during the talks, and specifically to confront every U.S. reference to paragraph 76(d) and to accept only paragraph 80(c) as a basis for MRIE:

> "We must make efforts not to depart from the clear legal basis of INFCIRC/153… we must particularly work towards resisting every reference from the U.S. side to… Article 76(d). Article 80(c) must be the sole basis for safeguards measures…"[152]

The German instructions, while noting that the UK was more interested in compromising with the Americans than the FRG, stated that the Parry Paper should only be modified in advance of the IAEA Working Group if the American paper was brought fully in line with the German

[150] Ibid.
[151] Ibid., 3.
[152] Original German: "Wir sollten uns bemühen, die sichere Rechtsbasis des INFCIRC 153 nicht zu verlassen… [i]nsbesondere muß darauf hingewirkt werden, daß jeder Bezugnahme auf den von US-Seite für… Artikel 76 d entgegengetreten wird. Artikel 80 c muß der alleinige Grund für Sicherheitskontrollen bleiben…" Wegener, "DE Nr. 2324 vom 29.5.72," BArch, B 72 (ZA)/105295 (May 31, 1972), 2.

INFCIRC/153 interpretation:[153] a tall order, ostensibly meaning that the United States would have to abandon its perimeter safeguards concept altogether.

Prior to the Brussels meeting, the UK government received a copy of the German instructions. the FRG's apparent reluctance to compromise instilled a degree of the same sentiment in the UK FCO. A telegram from the UK Embassy in Bonn commenting on the FRG position argued that a decoupling of GCEP safeguards from INFCIRC/153 could lead to a slippery slope that could make the Troika vulnerable to Soviet pressure at the IAEA Technical Working Group, and that the American "cops and robbers" approach could lead to the safeguarding of centrifuge manufacturing,[154] which was clearly out of bounds for INFCIRC/153 (although this would be addressed by the Model Additional Protocol, a quarter of a century later). The UKFCO response to this telegram argued, however, that compromise was in the UK's best interests, in this case, arguing that a display of transatlantic antipathy over GCEP safeguards would make it very difficult for the IAEA to uphold only the Troika position, regardless of its actual merit.[155] Furthermore, sticking to a legalistic interpretation of INFCIRC/153 could lead other States that the Troika was not interested in supporting the spirit of international safeguards.[156] At a tripartite meeting on June 7, 1972, the UK convinced the reluctant FRG government, as well as the less-reluctant Dutch government, to entertain the U.S. suggestions for concessions by either side.[157]

[153] Ibid., 2-3.
[154] UK Embassy Bonn to FCO, Telegram No. 768, TNA FCO 55/965/112 (June 5, 1972), 2.
[155] UK FCO to Embassy Bonn, Telegram No. 427, TNA FCO 55/965/117 (June 6, 1972), 1.
[156] Ibid., 2.
[157] UK FCO to UKDEL Brussels, Telegram No. 373, TNA FCO 55/965/120 (June 9, 1972).

Thus, the delegations at the Brussels meeting, unlike at the prior two quadripartite centrifuge safeguards meetings, entered the discussion with a newfound desire to reach a compromise – which was exactly what resulted. The United States agreed to remove statements that clashed with paragraph 76(d) and MRIE under paragraph 80(c) of INFCIRC/153 in its papers on GDP and GCEP safeguards (which had been previously shared with the UK), and reduced inspection effort levels in a third paper on IAEA safeguards at enrichment plants to levels near those in INFCIRC/153 paragraph 80(c).[158] In return, the Troika would eliminate references to INFCIRC/153 MRIE in the Parry Paper.[159]

As both the United States and the Troika agreed to keep their disagreement on inspection effort behind closed doors, the IAEA Technical Working Group took place without open confrontation between the attendees, which included representatives of the IAEA, Euratom, the United States, the UK, the Netherlands, the FRG, Japan, Australia, and South Africa. Although IAEA representatives voiced strong support for surveillance measures as a means for verifying the absence of clandestine enrichment activities at GCEPs, the United States did not advance the IAEA's argument any further, instead of arguing that due to the small size of the Almelo pilot plants, facility misuse was not a particularly pressing concern.[160] Meanwhile, although Euratom

[158] F. Brown, "Note for the Record: IAEA Working Group on Safeguards Procedures for Isotope Enrichment Facilities. Vienna, 12-16 June 1972," CW/39/126, TNA FCO 55/965/128 (June 20, 1972), 1.
[159] UK FCO to Embassy Vienna, Telegram No. 103, TNA FCO 55/965/121 (June 10, 1972).
The language that was removed from the Parry Paper read, "For a plant producing normally at more than 5% enrichment, the intensity of inspection calculated from the draft IAEA Safeguards Agreement is a minimum of 450 man-days per year." The following sentence was modified to read, "Under the assumptions of Appendix IV [covering frequency of random inspections], inspection intensity is likely in the near future to be in the range 100-200 man-days per year."
[160] U.S. Mission to the IAEA, IAEA Vienna 4201, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 24, IAEA 8-4: Technical Wrkg Grp, Safeguards Procedures for Isotopic Enrichment Facilities, 1972 (June 16, 1972).

disputed the idea of limiting inspector access to process areas,[161] the IAEA accepted the non-access safeguards concept without use of sophisticated containment and surveillance equipment, on the condition that technology currently at its disposal was sufficient.[162] The meeting did not recommend any specific measures to be applied to GCEPs. Instead the parties agreed to hold another meeting in 1-2 years, while continuing development, demonstrations and testing of equipment for non-destructive analysis, in collaboration with facility operators.[163] In this vein, the United States and the Troika agreed on an informal basis to jointly test safeguards instrumentation at Troika enrichment facilities.[164] The overall outcome was ideal for the Troika: the IAEA made no commitments to implement any of the aspects of the proposed U.S. approach (which had been toned down somewhat) that it found objectionable. Nick Fenn, in commenting on a summary note[165] on the proceedings of the Working Group by Fred Brown, a UK DTI official, wrote;

> "The outcome… is entirely satisfactory from our point of view… We have all worked hard for this. Dr. Brown must have played the hand in Brussels and Vienna with considerable skill and is to be congratulated… We now have 1-2 years to demonstrate that the technical judgement on which the Tripartite position was based is in fact correct. I hope it is!"[166]

At the same time, the United States was not discouraged by the Technical Working Group to give up its ambitious work on perimeter safeguards, which likely satisfied the U.S. delegation as to the

[161] Ibid.
[162] F. Brown, "Note for the Record: IAEA Working Group on Safeguards Procedures for Isotope Enrichment Facilities. Vienna, 12-16 June 1972," CW/39/126, 3.
[163] Ibid., 2.
[164] U.S. Mission to the IAEA, IAEA Vienna 4201 (June 16, 1972), 2–3.
[165] F. Brown, "Note for the Record: IAEA Working Group on Safeguards Procedures for Isotope Enrichment Facilities. Vienna, 12-16 June 1972," CW/39/126.
[166] N.M. Fenn, "Safeguards on Enrichment Plants," TNA FCO 55/965/W128 (July 18, 1972).

meeting's outcome. Nevertheless, U.S. and Troika intentions still could not have been more different on the development of perimeter safeguards, as Fenn wrote in October 1972:

> "I have the impression that the arrangement which emerged from the June Panel of the IAEA on Enrichment Plant Safeguards whereby the Americans would pursue their work on instrumentation is regarded by the tripartite partners as a sop to the Americans without immediate practical significance; but is regarded by the Americans as the major conclusion of the Panel. There are the seeds here of a misunderstanding which we should do what we can to avoid."[167]

As will be discussed later in this chapter, this misunderstanding did indeed emerge.

For the time being, however, a peaceful atmosphere had developed between stakeholders in GCEP safeguards. This situation, nevertheless, did not extend to the immediate interactions between Euratom and the Troika in the early 1970s. Euratom's aggressiveness on the issue of cascade access, along with Troika (and particularly West German) recalcitrance, would soon cause a four-month delay in signature of the IAEA-EURATOM safeguards agreement, under which all NPT comprehensive safeguards activities in EURATOM Member States would be governed. The following section details this episode.

[167] N.M. Fenn, "Safeguards on Enrichment Plants," TNA FCO 55/965/140 (October 18, 1972).

Cascade Access and the IAEA-Euratom Agreement

By July 1972, Euratom's had established that it considered that excess enrichment, as well as undeclared feed, were issues to be addressed by its safeguards activities, and that access to cascade halls would be necessary for accomplishing this. At this stage, however, Euratom had not yet clarified whether this access would need to be a one-off event, or whether it would need to be undertaken on a regular basis. Some safeguards activities, such as verification of the absence of underground clandestine piping installed in the foundation of a cascade hall (which was identified as a possibility in the Parry Paper),[168] could only take place on one occasion, in this case, prior to pouring of the concrete for the foundation. Indeed, before Spaak dispatched his July 1972 letter to UCN, Euratom inspectors had visited the Capenhurst pilot GCEP, and had been given access to the cascade hall prior to the installation of sensitive equipment.[169] It was unclear from Spaak's July 1972 letter,[170] however, whether cascade configurations, for example, would need to be re-verified on a regular basis. Upon receiving the letter, Nick Fenn, still at the UK FCO, interpreted Spaak's request as a one-off request, even though he assessed that "the Commission are taking an

[168] J.V.L. Parry, "The Safeguarding of Centrifuge Plants," as presented on March 29 in The Hague, BArch, B 196/10391 (March 29, 1972)

[169] F. Brown, "Tripartite Gas Centrifuge Project – Brief for the Joint Committee Meeting 17 November 1972," SK/11/01, TNA FCO 55/965/150 (November 9, 1972).

[170] F. Spaak to Prof. Bogaerdt, translated from Dutch into German, 105(ZA5)-2715/72, BArch, B 196/10391 (July 28, 1972), 2; In English: F. Spaak to Prof. Bogaerdt, translated from Dutch into English, TNA FCO 55/965/W13- (July 28, 1972), 3.

In the English translation, the reasons for cascade access are listed as the following:

- "to establish what process of enrichment is in fact being applied;
- to establish whether any enrichment capacity is available which has not been declared;
- to establish what degree of enrichment can be achieved, taking into account the various possibilities of controlling cascades;
- to check whether additional feed or production lines are available in the plant which have not been declared."

unacceptable position on this matter."[171] Fred Brown, in reply to Fenn, opined that Euratom was actually seeking routine cascade access, which would be needed to verify the absence of changes in operation of the GCEP.[172] This prospect, particularly in light of the June 1972 IAEA Working Group, which had concluded that cascade access, for the meantime, would not be necessary for effective safeguards, was unacceptable to the Troika.

As discussions within the UK Government over Euratom's access intentions were underway, negotiations towards the IAEA-Euratom safeguards agreement were drawing to a close. An agreement was made during this process, however, for the drafting of facility attachments (FAs) prior to signature of the agreement. Under this plan, Euratom would choose approximately ten facilities, for which FAs would be drafted.[173] Apparently, prior the close of negotiations, the production of FAs had not been expected to cause any problems or delays, although little work had been undertaken on this area at the time.[174] At the time the IAEA Board of Governors approved the agreement on September 22, 1972, hopes were high for getting the agreement signed quickly. The United States was especially hoping for a quick signature and ratification process, as the Soviet Union had already been criticizing the United States for making nuclear material exports to Euratom countries, which contravened the NPT, as those states had no comprehensive safeguards

[171] N.M. Fenn to F. Brown, "Centrifuge Safeguards: Euratom and Almelo," TNA FCO 55/965/136 (September 11, 1972).
[172] F. Brown to N. Fenn, "Safeguards on Gas Centrifuge Enrichment Plants," TNA FCO 55/965/138 (September 27, 1972).
[173] U.S. Mission to the IAEA, IAEA Vienna 7748, U.S. Mission to the IAEA, IAEA Vienna 4201, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 24, IAEA 8-4: Technical Wrkg Grp, Safeguards Procedures for Isotopic Enrichment Facilities, 1972 (November 3, 1972).
[174] U.S. Mission to the European Communities, EC Brussels 3424, RG 59, *Subject-Numeric Files, 1970-1973*, Box 2863, AE 13: EURATOM 6/1/72 (September 13, 1972).

agreement in force.[175] Signing of the agreement was initially expected to take place in mid-December 1972.[176]

The dispute between the Troika and Euratom over cascade access, however, meant that this smooth process did not materialize. As NPT NNWS subject to the IAEA-Euratom agreement, the Netherlands and the FRG (in particular) viewed the production of draft FAs prior to signature of the IAEA/Euratom agreement as an opportunity to produce an IAEA/Euratom FA for Almelo that explicitly did not allow for inspector access to the cascade halls.[177] The logic behind doing so was that an IAEA/Euratom FA without cascade hall access would serve as proof that effective comprehensive safeguards could be carried out without this access, and would thus make a compelling case that cascade access during Euratom inspections would not be justifiable. Given that the IAEA was not contesting the issue of cascade hall access at the time, there existed an opportunity for the technology holders to definitively resolve the question of cascade access. By November 1972, the West German Foreign Office had adopted an explicit policy not to sign the IAEA/Euratom safeguards agreement until an FA for Almelo had been drafted.[178] Meanwhile, officials at the U.S. State Department fretted about the delay, but were also constrained in coaxing the dispute towards resolution, given that the Troika and the United States had their own ongoing

[175] U.S. Department of State, "NPT Safeguards: Problems and Negotiations Which Lie Ahead," *Current Foreign Relations* 39, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 21, AE 13: Safeguards, General, 1972 (September 27, 1972).
[176] U.S. Mission to the European Communities, EC Brussels 4107, RG 59, *Subject-Numeric Files, 1970-1973*, Box 2863, AE 13: EURATOM 6/1/72 (October 27, 1972).
[177] U.S. Mission to the IAEA, IAEA Vienna 7748 (November 3, 1972).
[178] U.S. Mission to the European Communities, EC Brussels 4357, RG 59, *Subject-Numeric Files, 1970-1973*, Box 2863, AE 13: EURATOM 6/1/72 (November 10, 1972).

dispute over GCEP safeguards approaches, and thus the Troika nations were already sensitive about the United States trying to influence GCEP safeguards approaches to suit its own interests.[179]

The FRG and Dutch governments initiated a meeting with Euratom on November 27, 1972, during which both sides voiced their positions on cascade access. While the Member States voiced their frustration that the understandings reached at the Troika-Euratom May 17 meeting and the IAEA Working Group had not been heeded, Euratom argued that it would need more information on the design of the Almelo pilot plant before agreeing to a 'black box' safeguards approach.[180]As of November 1972, UCN had not yet provided Euratom with any design information for Almelo. H.W. Schleicher, the Head of Euratom Safeguards, clarified that the July 1972 Spaak letter was to be interpreted as a request for one-time access, but made no assurances on whether access would be requested at a later date.[181]

By the end of 1972, the situation had not improved. Although the number of draft FAs required for signature of the IAEA/Euratom agreement had apparently been reduced to six, and these documents had been completed, the FRG, in particular, was still insisting on an FA for Almelo.[182] At this point, the United States became concerned that the agreement would not be signed by the February IAEA BoG meeting,[183] at which the United States and Euratom members would be prone

[179] U.S. Mission to the European Communities, EC Brussels 4312, RG 59, *Subject-Numeric Files, 1970-1973*, Box 2866, AE 13: IAEA 8–11/72 (November 8, 1972); U.S. Department of State, State 204410, RG 59, *Subject-Numeric Files, 1970-1973*, Box 2863, AE 13: EURATOM 6/1/72 (November 8, 1972).
[180] L.F. Barclay, "Note of a Meeting on Safeguards on Centrifuge Enrichment Plants Between the Tripartite Governments (UK/Germany/Netherlands) and the European Commission on 27 November 1972 in Luxembourg," TNA FCO 55/965/159 (November 28, 1972), 3.
[181] Ibid., 3.
[182] U.S. Department of State, State 233602, RG 59, *Subject-Numeric Files, 1970-1973*, Box 2863, AE 13: EURATOM 6/1/72 (December 29, 1972).
[183] Ibid.

to criticism from the Soviet Union and its allies. Early in January 1973, however, at a demarche in Bonn at which the United States communicated its increasing concern over the delay, FRG officials stood by their demand for an IAEA/Euratom FA indicating levels of access and inspection effort for Almelo.[184] Meanwhile, with sights still set on signature by the February BoG meeting, an IAEA-Euratom meeting was planned for January 15-16, 1973, for finalizing the six FAs that had already been drafted.[185] At a Euratom Commission meeting approximately a week prior, the FRG continued insisting on a complete Almelo FA.[186] In response, Spaak proposed to the Euratom Member States that the "same degree of preliminary information" used for developing the other FAs should at least be provided for Almelo, prior to signature of the agreement.[187] This information would then be used to produce an 'example' FA for Almelo. The Euratom Member States agreed to respond to this proposal prior to the January 15-16 meeting, thus forcing the Netherlands and the FRG to declare exactly what they wanted to be included in the Almelo FA.[188] This proposal was accepted by both the Netherlands[189] and the FRG,[190] after which the FRG only required invocation of INFCIRC 153 para. 46(b)(iv) on special material balance areas, and estimates of IAEA and Euratom inspection effort in the example FA.[191] Furthermore, and perhaps most importantly, the FRG and the Netherlands sent communications to the Euratom Commission with the assurance that limitations on IAEA/Euratom access under paragraph 46(b)(iv) would not limit

[184] U.S. Embassy Bonn, Bonn 78, RG 59, *Subject-Numeric Files, 1970-1973*, Box 2863, AE 13: EURATOM 6/1/72 (January 3, 1973).
[185] U.S. Mission to the European Communities, EC Brussels 106, RG 59, *Subject-Numeric Files, 1970-1973*, Box 2863, AE 13: EURATOM 6/1/72 (January 9, 1973).
[186] Ibid.
[187] Ibid.
[188] Ibid.
[189] U.S. Mission to the European Communities, EC Brussels 192, RG 59, *Subject-Numeric Files, 1970-1973*, Box 2863, AE 13: EURATOM 6/1/72 (January 15, 1973).
[190] U.S. Mission to the European Communities, EC Brussels 220, RG 59, *Subject-Numeric Files, 1970-1973*, Box 2863, AE 13: EURATOM 6/1/72 (January 16, 1973).
[191] U.S. Mission to the IAEA, IAEA Vienna 657, RG 59, *Subject-Numeric Files, 1970-1973*, Box 2866, AE 13: IAEA, 4–6/73 (January 29, 1973).

rights of Euratom under the Euratom Treaty,[192] thus separating the issue of inspector access under IAEA/Euratom safeguards, from access under Euratom safeguards.[193] By the end of January 1973, constructive negotiations were under way towards an 'example' Almelo FA for IAEA/Euratom safeguards. At these talks, the IAEA Inspector General[194] Rudolf Rometsch explicitly withheld reservations to limits on IAEA access to parts of an enrichment facility.[195] Thus, although an example FA had not been completed and the IAEA/Euratom agreement had not been signed by the February IAEA BoG meeting, at least Euratom could report at the BoG that genuine progress was being made on this item.[196]

An IAEA/Euratom example FA for Almelo was finally completed in March 1973, and the IAEA/Euratom agreement was finally signed soon after, on April 5, 1973.[197] The example FA agreed for Almelo, in 4 pages (at least in the German version), indeed satisfied the West German conditions for giving no access for IAEA inspectors to the cascade halls, and inspection effort estimates for both the IAEA and Euratom inspectors.[198] Although this FA had no legal standing,

[192] This logic, of course, is legally valid, as restrictions of inspector access to protect information (under INFCIRC/153) do not apply to Euratom Treaty safeguards, as no provisions for this exist in the latter.
[193] U.S. Mission to the IAEA, IAEA Vienna 657 (January 29, 1973).
[194] The title of Inspector General preceded the title of Deputy Director General for Safeguards at the IAEA. The IAEA Inspector General was directly subordinate to the Director General, and was responsible for all IAEA safeguards activities.
[195] U.S. Mission to the IAEA, IAEA Vienna 693, RG 59, *Subject-Numeric Files, 1970-1973*, Box 2866, AE 13: IAEA, 4–6/73 (January 30, 1973).
[196] U.S. Mission to the European Communities, EC Brussels 508, RG 59, *Subject-Numeric Files, 1970-1973*, Box 2866, AE 13: IAEA, 4–6/73 (January 31, 1973).
[197] David A.V. Fischer, "IAEA/EURATOM Agreement – An Explanation," *IAEA Bulletin* 15, no. 3 (June 1973): 10–16.
[198] Commission of the European Communities, "Mitteilung der Kommission und Entwurf eines Beschlusses des Rates zur Billigung der "ergänzenden Abmachungen" des Übereinkommens zwischen dem Königreich Belgien, der Bundesrepublik Deutschland, der Italienischen Republik, dem Großherzogtum Luxemburg, dem Königreich der Niederlande, der Europäischen Atomgemeinschaft und der Internationalen Atomenergie-Organisation in Ausführung von Artikel III, Absätze 1 und 4 des Vertrages über die Nichtverbreitung von Kernwaffen," Attachment 1, KOM(73) 363 (final version), PA AA, B 72 (ZA)/114137 (March 14, 1973).

as the Euratom Member States not yet ratified the NPT, no less the IAEA/Euratom safeguards agreement, it can nevertheless be argued that this document did by its nature establish some precedent on gas centrifuge safeguards (beyond that which had already been set by the 1972 IAEA Working Group and STR-14). True to the Parry Paper's model, material balance was the only order of business – no reference is made anywhere to verifying the absence of facility misuse. The document also established a very low and narrow level of inspection effort for the IAEA, both in an absolute sense, and relative to Euratom. Over an annual period, Euratom would expend between 126-136 PDIs, while the IAEA inspectors would only spend 55-70 PDIs, as shown in Table 4-4, which also provides an itemized listing of activities for each inspectorate.[199] These levels of inspection effort, however, when compared with throughput for the plants specified in the document, yield an interesting observation. Ignoring the fact that the mass of feed does not match up with the combined product or tails masses, it can be shown (as in Table 4-5) that about 9 ekg of feed enters the plant each year, and about 17 ekg of product and tails leave the plant each year, using the number, weights, and enrichments of cylinders specified in the FA. Taking the higher value, 17 ekg, as the plant's throughput, the paragraph 80(b) and 80(c) MRIE values for the plant would be 124 and 107 PDIs respectively. Clearly, the expected total average routine inspection effort between the IAEA and Euratom exceeds even the higher INFCIRC/153 MRIE value. However, given that Article 80 of the IAEA/Euratom agreement, INFCIRC/193 (which corresponds to paragraph 80 of INFCIRC/153) applies only to IAEA inspections,[200] the inspection

[199] Ibid., 3–4.

[200] Articles 70-90 of INFCIRC/193 provide a legal framework for IAEA inspections under the IAEA/Euratom agreement. Specific measures listed in these paragraphs, in general (including in Article 80), apply only to IAEA inspections. See: "The Text of the Agreement Between Belgium, Denmark, The Federal Republic of Germany, Ireland, Italy, Luxembourg, The Netherlands, The European Atomic Energy Community and the Agency in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons," INFCIRC/193, (Vienna: International Atomic Energy Agency, September 14, 1973).

effort given in the example FA would comply with the lower MRIE limit, as desired by the Troika. Nevertheless, with this observation in mind, it is unclear how the MRIE limit would be satisfied if the same safeguards measures were to be conducted in a non-Euratom state, leaving the IAEA to carry out all verification activities itself. As Japan started constructing its own pilot GCEP in the second half of the 1970s, the IAEA would have to revisit this question. On the whole, this example FA reflected a bare-bones safeguards approach, in line with the Troika's vision.

Table 4-4: Average Routine Inspection Effort figures for the March 1973 'example' IAEA/Euratom Facility Attachment for the Almelo pilot facilities (combined). Translated by author from German. Source: Commission of the European Communities, "Mitteilung der Kommission…," Attachment 1, KOM(73) 363 (final version), PA AA, B 72 (ZA)/114137 (March 14, 1973), 3–4.

Summary of Yearly Average Routine Inspection Effort (ARIE)	
1. Euratom Tasks	**Person-days of Inspection/year**
Incoming feed	- (x)
Containers with incoming feed – weighing and sampling	- (x)
Disconnection of empty feed containers and connection of full feed containers	64
Disconnection of full product containers and connection of empty product containers	6 (xx)
Disconnection of full tails containers and connection of empty tails containers	31
Weighing and sampling of product and tails containers (40x/year)	- (x)
Physical inventory verification (1x/year)	10-20
Interim material balance closing (3x/year)	15
Waste measurements	- (xx)
Materials accountancy checks, maintenance of installed verification equipment, if present	- (xx)
Total Inspection Effort	**126-136**
2. IAEA Tasks	**Person-days of Inspection/year**
Physical inventory closing, as well as measurements on waste	5-10
Interim material balance closing	10
Determination of product and tails enrichment, verification of feed	40-50
Total Inspection Effort	**55-70**

(x): Inspection effort to be minimized through coordination and planning by the facility operator.
(xx): Coincides with other activities.

Table 4-5: Calculations of throughput, in effective kilograms, for the feed, product, and tails lines at the Almelo pilot plants, using information provided in the March 1973 'example' IAEA/Euratom Facility. EKG, as per INFCIRC/153, paragraph 104, are calculated for uranium in the following way, where x is enrichment and m is uranium mass:

$x \leq 0.005$: EKG = 0.00005m;
$0.005 < x < 0.01$: EKG = 0.0001m;
$x \geq 0.01$: EKG = mx^2

Sources: Commission of the European Communities, "Mitteilung der Kommission…," Attachment 1, KOM(73) 363 (final version), PA AA, B 72 (ZA)/114137 (March 14, 1973), 3–4; INFCIRC/153 (corr.), para. 104.

	Number of UF_6 cylinders	Cylinder capacity (kg UF_6)	Enrichment	Total mass (kg U)	Effective kilograms
Feed	64	2177	0.007	94202	9.42
Product	3.5 (Plant A)	2177	0.035	5151	6.31
	6.5 (Plant B)	2177	0.026	9567	6.47
Tails	23 (Plant A)	2177	0.0026	33854	1.69
	8 (Plant B)	9500	0.00325	51386	2.57

The resolution of the Troika-Euratom dispute over cascade access in early 1973, however, was a short-lived victory. Merely a few months later, Euratom would again challenge its Member States over access rights, and this second time, the united front that the Troika had maintained up to that point would fail.

The Euratom-Troika Cascade Access Battle, Round 2

While Euratom leadership displayed some willingness to treat the possibility of a cascade exclusion area as a "working hypothesis," as was implicit in the 'example' FA, Euratom remained committed to retaining its right to access all facility areas, if necessary.[201] By the late spring 1973, the first routine Euratom inspection of Almelo was looming close. Earlier that year, Euratom delivered a working document to the Dutch government, dated April 6, 1973 (one day after

[201] U.S. Mission to the IAEA, IAEA Vienna 8720, RG 59, *Subject-Numeric Files, 1970-1973*, Box 2863, AE 13: EURATOM 6/1/72 (December 14, 1972), 2.

signature of the IAEA-Euratom agreement!), which reiterated the Euratom position that access to centrifuges would be required.[202] The impending inspection was discussed at a Junior Joint Committee (JJC) meeting in May 1973,[203] during which a Dutch representative suggested allowing the Euratom inspectors to make a one-time visit to the sensitive portions of the plant.[204] Other members of the JJC (i.e. FRG and British members) and Urenco personnel, however, resisted the idea, as centrifuges bearing sensitive information were already installed at Almelo.[205] In early July 1973, in preparation for the inspection, which had been scheduled for July 17-22, the Dutch government drafted a rather blunt letter to Euratom outlining the Troika's opposition to any cascade hall access provision, relying on the argument that access to cascade halls was not necessary for fulfilling safeguards provisions, specifically Article 77(a) of the Euratom Treaty (according to the Troika's definition). The communication perhaps belied a degree of frustration, stressing that the three governments had brought up this argument repeatedly up to the present time.[206]

But while the letter argued strongly against cascade hall access, it did recognize that Euratom possessed the legal right for unlimited access[207] under Article 81. Thus, the Troika's entire argument was based on the premise that visiting sensitive portions of Almelo would be

[202] van de Winkel to Keltsch and Brown, draft telegram, BArch, B 196/10391 (July 3, 1973).
[203] The Junior Joint Committee was formed as an informal counterpart to the Tripartite Joint Committee, for considering issues relevant to Urenco and Centec at a more technical level.
[204] Tripartite Junior Joint Committee, "Results of the meeting of the "Junior Joint Committee" on 24th May 1973 in Bonn," BArch, B 196/10387 (May 28, 1973), 8.
[205] Ibid.
[206] Original Dutch: "Zoals in het verleden reeds herhaaldelijk door vertegenwoordigers van de drie regeringen naar voren is gebracht in besprekingen met vertegenwoordigers van uw dienst, zijn deze van oordeel dat een ongelimiteerde toegang tot de scheidings-installaties op dit moment niet noodzakelijk is om de ertsen, grondstoffen en bijzondere splijtstoffente controleren en er zich van te vergewissen of de bepalingen an artikel 77(a) van het Euratom-verdrag worden nageleefd. van de Winkel to Keltsch and Brown, BArch, B 196/10391 (July 3, 1973), 2.
[207] Ibid., 4.

unnecessary for the purposes of Euratom safeguards. In light of this, the Troika requested that Euratom refrain from requesting cascade hall access during the upcoming inspection, and to revisit the issue if Euratom found that their degree of access during the visit was insufficient.[208]

In this case, Euratom decided to follow along with the Troika's request, instructing its inspectors not to attempt cascade hall access during the July 1973 inspection, and that the Euratom Commission would evaluate whether this access would be required, following the inspection.[209] In listing the goals of the inspection in this letter, however, a need for cascade hall access seemed implicit, as Euratom sought to determine how cascades might be reconfigured for producing undeclared enrichment levels, as well as the absence of undeclared enrichment capacity.[210] A diplomatically written report by the two Euratom inspectors carrying out the visit, W. Klöckner and E. van de Stijl (presumably German and Dutch nationals, respectively), indicates that the inspection went smoothly without cascade access. This report argued that the absence of undeclared enrichment capacity or undeclared excess enrichment could be verified via material balance calculations.[211] As for design characteristics of the enrichment plant, the inspectors wrote that the separative capacity of the plant could be calculated by comparing its electricity consumption against public figures on centrifuge power consumption, and maximum separative capacity at the plant could be determined from material balance at the plant. According to the inspectors, verifying the absence of undeclared feed, which could be used to disguise undeclared

[208] Ibid., 6.
[209] J.H.L. van de Mortel to W. Pabsch, "Inspektion U.C.N. und Uranit-Anlagen zu Almelo," BArch, B 196/10391 (July 18, 1973), 1–2.
[210] Ibid., 2.
[211] "Inspektion der Demonstrations-Anlage UTA 25, Almelo und er U.C.N. Almelo am 17.7. bis 19.7.1973" (July 19, 1973), 2, attachment to Meysenburg and Kraska to Heil, "Euratom-Inspektion in Almelo, PA AA, B 72 (ZA)/114137 (July 25, 1973).

enrichment capacity or over-enrichment, could be accomplished by a patrol of open areas,[212] seemingly ignoring the possibility that undeclared material could exist in sensitive areas of the plant, or that it could enter the cascade area via hidden piping. The tone and content of the letter reflect a degree of naïveté on the inspectors' part. Power consumption of centrifuges versus their separative capacity, for example, can change as new generations of centrifuges are installed at a plant (while verifying the models of centrifuges in the sensitive area would be impossible), and relying on material balance for detecting plant misuse is only tenable if the absence of undeclared feed material is assumed. It is worth wondering if this report, despite its optimistic tone, was actually intended to demonstrate that Euratom's GCEP safeguards measures, without cascade hall access, would be inadequate, or perhaps that the inspectors, likely lacking technical knowledge of the centrifugation process, had been fed information to report back to Euratom Headquarters by Almelo personnel.

Euratom management was nevertheless dissatisfied with the results of the inspection. Fernand Spaak voiced Euratom's disapproval to the Dutch government in an October 1973 letter. The Dutch Ministry of Foreign Affairs passed an unofficial English translation of this letter to the UK FCO. Although Euratom had yielded to the Dutch government's request during the July 1973 inspection, Spaak underlined the fact that Euratom held the prerogative on "whether inspection of a specific nature is necessary or not,"[213] as per the English translation. Spaak's main point, as translated, read:

[212] Ibid., 1.
[213] Bosscher to Illman, Telegram, BArch, B 196/10388 (November 12, 1973).

> "I have the honour to inform you that the Commission is unable to accept the arguments advanced since they are mainly based on the hypothesis that non-declared substances are not present, so that inspection is confined to merely recording the declarations made by the parties concerned."[214]

Thus, Spaak yet again argued that inspectors would need to visit the cascade halls in order to verify and periodically re-verify the design characteristics of the facility (as had been attempted more than a year prior).[215] At the end of the letter, Spaak announced that Euratom would make a "fresh inspection" at both Almelo pilot plants, and that cascade access would be required on this occasion.[216]

The next Euratom inspection was scheduled for November 13-15, 1973. True to Spaak's promise, the inspectors requested cascade hall access on the first day of the inspection.[217] Oddly, it seems that neither the Troika nor Urenco/UCN had not yet agreed on a response to the inspectors' requests, even though Euratom had clearly voiced its desire to visit the cascade hall at Almelo for over a year. It is possible, however, that this particular inspection caught the Dutch by surprise, as Euratom had only informed the Netherlands on November 6 of its intent to visit Almelo on those dates.[218] In addition to this, perhaps Almelo's management, encouraged by positive results conveyed by Euratom inspectors after the July 1973 inspection, believed that Euratom would refrain from requesting cascade access in the future, and did not see it necessary to prepare for further access demands.

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[214] Ibid., 2.
[215] Ibid.
[216] Ibid., 3.
[217] J.E.E. Meilof, "Report on Euratom inspection held on 13, 14 and 15 November 1973," BArch, B 196/10391 (November 19, 1973).
[218] Netherlands Ministry of Foreign Affairs to Dutch Permanent Representative in Brussels, unofficial English translation, B 196/10391 (November 12, 1973).

One day before the inspection took place, the Netherlands attempted to delay the inspection, complaining that Spaak had not provided any reasons for access in his most recent letter.[219] This statement, although factually correct, seems odd, given that Euratom had clearly stated its reasons for cascade hall access in prior correspondence (e.g. Spaak's letter from July 28, 1972), although the superficially positive and perhaps ill-informed report from the July 1973 inspection may have clouded the waters as to whether satisfactory safeguards could be achieved without cascade access. In any case, Euratom did not heed the Dutch request, and the inspection, conducted again by Klöckner and van der Stijl, began as scheduled.

The Almelo plant manager, J.E.E. Meilof, first sought to delay the inspectors' attempt to access the cascade halls by requesting that they reserve their visit to the cascade hall as their last order of business.[220] The inspectors acceded to the request. Over the next two days, the Troika governments, along with the Urenco stakeholders UCN and Uranit, scrambled to come up with a plan. Up to this point, they had succeeded at keeping Euratom out of Almelo's cascade halls, arguing that access was unnecessary, and had seemingly convinced individual Euratom inspectors that this was the case. Euratom had the prerogative to determine whether this was the case, however, and now Euratom was demanding access. Following the request, the Dutch Ministry of Foreign Affairs feared that a direct government order to bar the inspectors could land the Netherlands in court,[221] as this could be construed as a violation of the inspector access provision in the Euratom Treaty.

[219] Ibid.
[220] Meilof, "Report on Euratom inspection held on 13, 14 and 15 November 1973," BArch, B 196/10391 (November 19, 1973), 2.
[221] Karl Keltsch, "Euratom-Inspektion in den Zentrifugenanlagen Almelo," Memorandum, PA AA, B 72 (ZA)/114137 (November 14, 1973), 2.

Thus, the Dutch considered leaving the decision on access up to UCN and Uranit, distancing itself from any action that could be considered non-compliant with the Euratom Treaty. However, a German JC representative, Karl Keltsch, also an official at the recently created Federal Ministry of Research and Technology (BMFT)[222] advised the Dutch government on November 14 not to delegate the decision, for the sake of preserving the internal policymaking relationship between the Troika governments, and instead to admit the inspectors to the cascade areas under protest and to report its displeasure to the Euratom Commission.[223] That afternoon, the Dutch government made a decision. Amazingly, the Netherlands decided to concede entirely to Euratom, admitting the inspectors without protest. In a telephone call with the European Commission, the Dutch Ministry of Foreign Affairs acknowledged that UCN and Uranit had refused the Euratom inspectors entry to cascade areas, but emphatically stated that the Government of the Netherlands had not ordered UCN or Uranit to do so.[224] In addition, the Dutch government reiterated its acknowledgement from its July letter,[225] stating that Euratom inspectors had the right to access all locations, data and persons necessary for carrying out safeguards pursuant to Article 77(a) of the Euratom Treaty.[226] In closing, the Netherlands stated that it would not neglect to inform UCN and Uranit of the current situation.[227] In this communication, the Dutch government clearly did not invoke any form of protest, but did not voice any judgment, positive or negative, as to whether the access was necessary under Article 77. An affirmation of the necessity of cascade hall entry would

[222] The BMFT oversaw centrifuge enrichment development in the FRG from 1972 onwards.
[223] Keltsch, "Euratom-Inspektion in den Zentrifugenanlagen Almelo,"November 14, 1973, 2.
[224] Dutch Ministry of Foreign Affairs to Standing Representative of the Netherlands to the European Communities, "Inspektion UC-Installation zu Almelo," Unofficial translation from Dutch into German, PA AA, B 72 (ZA)/114137 (November 14, 1973).
[225] van de Winkel to Keltsch and Brown, BArch, B 196/10391 (July 3, 1973), 4.
[226] Dutch Ministry of Foreign Affairs to Standing Representative of the Netherlands to the European Communities, "Inspektion UC-Installation zu Almelo," Unofficial translation from Dutch into German, PA AA, B 72 (ZA)/114137 (November 14, 1973).
[227] Ibid.

certainly anger the FRG (and probably the United Kingdom), which would in the future take a harder-line approach to the access question.

By November 15, still no decision had been had communicated to Almelo. The Urenco shareholders, meanwhile, had been doing their best to forestall the inspection up to the very last day, telling Klöckner and van der Stijl that they would need a "clearance certificate" from the Dutch government to gain entry to the cascade area.[228] UCN, on November 15, inquired with the Dutch Ministry of Economic Affairs as to whether this certificate had been granted.[229] By this time, of course, the government had made a decision. Meilof received a telegram from the Ministry of Foreign Affairs at 4:47 PM, advising that cascade access be granted.[230] The Euratom inspectors subsequently visited the cascade halls in both the Dutch and German pilot plants.[231] In the Dutch facility, inspectors performed gamma spectrometry measurements to verify that only small amounts of uranium were present in the cascade hall, and assessed how changes to piping arrangements might be made, and estimated the "approximate output of a centrifuge."[232] Upon leaving, the inspectors stated that they were "satisfied" with the course of the visit.[233]

British and West German officials were incensed by the Dutch government's actions. Keltsch complained, in a memorandum, that the decision by Dutch Ministry of Foreign Affairs ran against

[228] Meilof, "Report on Euratom inspection held on 13, 14 and 15 November 1973," BArch, B 196/10391 (November 19, 1973), 2.
[229] Karl Keltsch, "Euratom-Inspektion in den Zentrifugenanlagen Almelo," Memorandum, PA AA, B 72 (ZA)/114137 (November 16, 1973).
[230] Meilof, "Report on Euratom inspection held on 13, 14 and 15 November 1973," 2.
[231] Keltsch, "Euratom-Inspektion in den Zentrifugenanlagen Almelo," 2.
[232] Meilof, "Report on Euratom inspection held on 13, 14 and 15 November 1973," 2–3.
[233] Ibid., 3.

the FRG's interests, and was undertaken without approval of the UK.[234] The minutes of a JJC meeting on December 7, 1973 states, "The British and German delegations regretted that this inspection had not been prevented."[235] Representatives from the UK, which had joined Euratom at the beginning of 1973, stated (with the support of the FRG) that Euratom inspectors would not be allowed in cascade areas at Capenhurst cascade area, and that the UK would be willing to take the matter to court.[236] At a JC meeting two weeks later, however, the Dutch delegation voiced reluctance to support British efforts to restrict inspector access, arguing that in the recent Almelo inspection, "legally there would have been no case to fight."[237] This reasoning was based on the Euratom prerogative for requesting Article 81 access to facilities, and that under Article 10 of the Treaty of Almelo, Euratom Treaty obligations took precedence over those in the Treaty of Almelo (including access restrictions for uncleared visitors).

Within UK government circles, officials were harshly critical of the Dutch decision. In the aftermath of the inspection, a UK DTI official, C. Herzig, complained that the Dutch "chose to ignore" the UK and FRG position, and observed that in the long term, it would be difficult to refuse Euratom inspectors access to the Capenhurst gas centrifuge enrichment plant, which was now subject to Euratom safeguards as well.[238] Indeed, two years later, as Euratom was preparing to undertake its first inspection at the Capenhurst GCEP, Fred Brown, now at the UK Department of

[234] Keltsch, "Euratom-Inspektion in den Zentrifugenanlagen Almelo," 1.
[235] Tripartite Junior Joint Committee, "Results of the third JJC-meeting on 5th Dec. 1973 in Bonn," JC/SEC/30/73, BArch, B 196/10388 (December 7, 1973), 2.
[236] Ibid., 3.
[237] Tripartite Joint Committee, "Summary minutes of the 11th Joint Committee meeting held in Bonn on 20th December, 1973," JC/D/74/1. BArch, B 196/10388 (March 8, 1974), 7.
[238] C. Herzig, "EEC Inspection of Almelo Plants and your Telex of 19 11 73," TNA FV 70/17/2/13 (November 26, 1973).

Energy (UKDOE),[239] noted "the Tripartite position was completely undermined by the Dutch decision to allow Euratom inspectors into the cascade halls at Almelo."[240] Approximately one week after the inspection, Dutch embassy officials spoke with Nick Fenn at the UKFCO to explain the events that transpired, explaining that the Dutch government still believed that cascade access was unnecessary, but that the Dutch government was bound legally to grant access to the Euratom inspectors.[241] Fenn, however, made no effort to disguise his perspective on what had happened, writing that one of the Dutch officials "nodded wisely at every point I made and clearly thought that his Government had been unnecessarily spineless."[242]

This episode, in the end, marked the breaking down of the 'barn door' for cascade hall access, in the case of Euratom inspections at Troika GCEP facilities. The decision of the Dutch government to admit Euratom inspectors to the Almelo cascade halls established Euratom's right to do so upon its own judgment. Backtracking on this decision after the fact, as the Dutch government had observed, would have been difficult, particularly from a legal perspective. Thus, from 1974 onwards, Euratom inspectors were allowed access to cascade areas at Almelo.[243] It is unclear exactly how frequent Euratom inspections were – a 1975 cable from U.S. Mission to the IAEA remarked that to its knowledge, Euratom had not applied safeguards at Almelo (contrary to events

[239] The UK Department of Energy was established in January 1974, taking over the UK DTI's energy portfolio (including uranium enrichment issues).
[240]F. Brown to P.I.M. Irwin, "Access to Centrifuge Enrichment Facilities," TNA FV 70/17/1 (March 15, 1976), 1; See also W.C. Fitzsimmons (UK Department of Energy) who wrote, "our position has been substantially weakened by the access already permitted at Almelo," W.C. Fitzsimmons to D.C. Fakley, "Access to Centrifuge Plant at Capenhurst," TNA FV 70/17/1 (July 2, 1975).
[241] N.M. Fenn to J.J. d'A. Collings, "Euratom Safeguards: Access to Almelo," TNA FV 70/17/2/21 (December 5, 1973).
[242] Ibid., 2.
[243] Here, reference is only made to inspections carried out solely by Euratom inspectors. IAEA-Euratom inspections at Almelo would not begin until 1979 (at which point they took place on an ad-hoc basis) and did not feature cascade hall access until adoption of the HSP approach in 1983.

two years prior).[244] Nevertheless, during Troika preparations for HSP negotiations towards an IAEA GCEP safeguards approach, a Dutch representative announced, "the Netherlands from the very beginning of the Euratom safeguards inspections have accepted that, on the basis of [Euratom Treaty] article 81 sub 2, Euratom inspectors are entitled te [sic.] access to the cascade halls."[245] By informal agreement, however, the nationalities of these inspectors were limited only to those of the Troika countries, thus mitigating concerns over the spread of sensitive design information.[246]

The Dutch unilateral decision to grant cascade access to Euratom inspectors, in retrospect, carried two important implications, as viewed in retrospect. First, this event was, in a sense, a harbinger of Troika disunity over the same issue in the late 1970s and early 1980s, when cascade access became a matter of dispute in the context of IAEA safeguards activities. Previously, the Dutch government had stuck with the tripartite line on GCEP safeguards issues. Nevertheless, it is not particularly surprising that the Dutch yielded first to Euratom pressure, given that the facility in question was physically located in the Netherlands. Although each State in the Troika had an incentive to abide by the group's official position on cascade access, only the Dutch were legally responsible for safeguards issues at Almelo. If inspector access was inhibited and the European Commission were to challenge this in court, the case would be primarily answerable by the Netherlands, and not the FRG nor the UK. Thus, a convincing argument can be made that the threat of legal action by Euratom was far more pressing for the Dutch than for other members of the Troika, and that for this reason, criticism of the Dutch Government being "spineless" has a

[244] U.S. Mission to the IAEA, IAEA Vienna 7658, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (September 8, 1975), 2–3.
[245] L.G. Wansink, Memorandum in preparation for Tripartite Joint Committee Meeting, PA AA, B 72 (ZA)/129441, (February 15, 1981), 1.
[246] Gerstler, "Empfehlungen von Überwachungskonzepten (Safeguards-konzepte) für Zentrifugenanreicherungsanlagen," Memorandum, PA AA, B 72 (ZA)/129441 (February 16, 1982), 2.

hollow ring, given that the UK would not have been legally responsible for the inhibition of Euratom access on Dutch soil. Indeed, by early 1976, when faced with the same question at the Capenhurst GCEP, the UK government recognized the fact that the European Commission would probably win a legal case over the issue of cascade access, and that being taken to court would lead to an unfavorable situation in which Euratom inspectors would have essentially unlimited access to all areas of the plant.[247] Under this consideration, the UK instead sought to negotiate a compromise featuring limitations on Euratom access,[248] unlike the Dutch decision to immediately open the floodgates.

The second issue raised by Euratom's success at gaining cascade access was the creation of two conflicting precedents over cascade access, which would cause conflict among inspectorates and Member States in later years. By undertaking access to cascade halls, Euratom was implicitly demonstrating that this access was necessary under Article 81 of the Euratom Treaty in the implementation of effective safeguards, particularly for verifying design information (for example, using the reasons listed in Spaak's July 1972 letter as a reference). Meanwhile, the IAEA had committed itself, at least as a working hypothesis, to non-access GCEP safeguards approaches and the use of traditional safeguards methods. Thus, when cascade access for the IAEA came into question, stakeholders on either side of the debate could point to the precedent of Euratom's safeguards activities, which featured unlimited cascade access, or to the IAEA's original approach, which excluded inspector access to cascades entirely. In this sense, Euratom's victory in the battle

[247] F. Brown to D.C. Fakley, "Access to Centrifuge Enrichment Facilities," TNA FV 70/17/1 (February 19, 1976).
[248] No agreement was reached under this initiative, nevertheless, leaving the question of inspector access at Capenhurst unresolved until the end of the HSP. See Fred Brown to Peter Kelly, "The Hexapartite Safeguards Project (HSP): Tokyo Meetings 4-13 November 1981," TNA FCO 96/1465/91 (November 19, 1981).

to access the Almelo cascade halls, although certainly well-intended on Euratom's part, led to complications in agreeing on an IAEA-Euratom safeguards approach for the same site in later years.

More False Starts in U.S.-Troika Technical Cooperation

By the time an IAEA-Euratom safeguards approach was considered for Almelo in the late 1970s, on the tails of the entry into force of the IAEA-Euratom agreement in 1977, little progress had been made on the development of safeguards technology for GCEPs. Even though the United States had been ambitious in designing its original approach, a lack of Troika receptiveness in cooperating with the United States stymied further GCEP safeguards technology development. This likely added further to difficulties in agreeing to a tenable approach, prior to the beginning of the HSP, as insufficient technical understanding of GCEP safeguards measures existed at that time.

The seed of U.S.-Troika technical cooperation was sown at the IAEA June 1972 Working Group, during which the United States and the Troika countries agreed on an informal basis to jointly test safeguards instrumentation at Troika enrichment facilities.[249] In particular this study group would examine the issue of perimeter control for GCEP safeguards. While it is clear that the Troika States were staunchly opposed to deployment of perimeter surveillance, their participation would have been incentivized by the ability to closely observe and shape the development and capabilities of this system, which was heavily favored by the Americans, while the United States would be able

[249] U.S. Mission to the IAEA, IAEA Vienna 4201, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 24, IAEA 8-4: Technical Wrkg Grp, Safeguards Procedures for Isotopic Enrichment Facilities, 1972 (June 16, 1972). 2-3.

to develop the technology in a real-world environment. Thus, despite the strife between the two sides over the issue, the joint development program was arguably an effort that could have benefitted both sides. In December 1972, a formal invitation to the Troika was transmitted from the U.S. State Department Bureau of International Scientific and Technological Affairs.[250] Along with the formal invitation, the United States sent two papers authored by Herb Kouts, of Brookhaven National Laboratory (the same Herb Kouts that was perceived by IAEA officials to be driving the hardline U.S. position, as mentioned earlier in this chapter).

One of these papers gave details on a reference enrichment plant used by the United States for conceptualizing its safeguards systems, while the other paper outlined U.S. plans for development of a perimeter safeguards system. The reference plant, as presented in the Kouts Paper, consisted of a process area surrounded by a perimeter fence, with support buildings and storage areas for UF6 cylinders outside the fence. The process area would include a cascade building, with rooms containing the feed and takeoff areas, as well as a waste storage area at the periphery of the cascade building. Structures outside the fence, in addition to the UF6 cylinder storage area, would include a weighing and sampling area, and analytical laboratory, and an administration building. The fence would feature two portals, one for personnel, and one for vehicles. Key measurement points (KMPs) for inventory would be located at all of the feed and takeoff points, as well as the waste storage area, and the cylinder storage yard. Flow KMPs would include the two portals in the fence, as well as the sampling area and analytical lab. To verify the absence of undeclared material in the process area, constant surveillance would take place on nuclear material, other items, vehicles and

[250] H. Daniel Webster to van Vierssen, U.S. Department of State Bureau of International Scientific and Technological Affairs (December 8, 1972), enclosure to L.M.J. van de Winkel to Members of the Centrifuge Joint Committee, JC/SEC/72/39, BArch, B 196/10391 (December 20, 1972).

personnel entering and leaving the two portals.[251] Inspectors, thus, would be allowed to enter inside the surveillance fence, but only to perform measurements at the inventory KMPs inside feed/takeoff and waste areas, and not to access the cascade hall. In sum, the Kouts concept was essentially identical to the second perimeter safeguards concept considered in the 1972 Bengelsdorf paper.[252] A schematic of the Kouts reference facility, directly lifted from the document, is given in Figure 4-2. The capacity of the Kouts reference facility was considered to be 200 tSWU/yr, identical in size to the demonstration-scale plants planned at Almelo and Capenhurst.

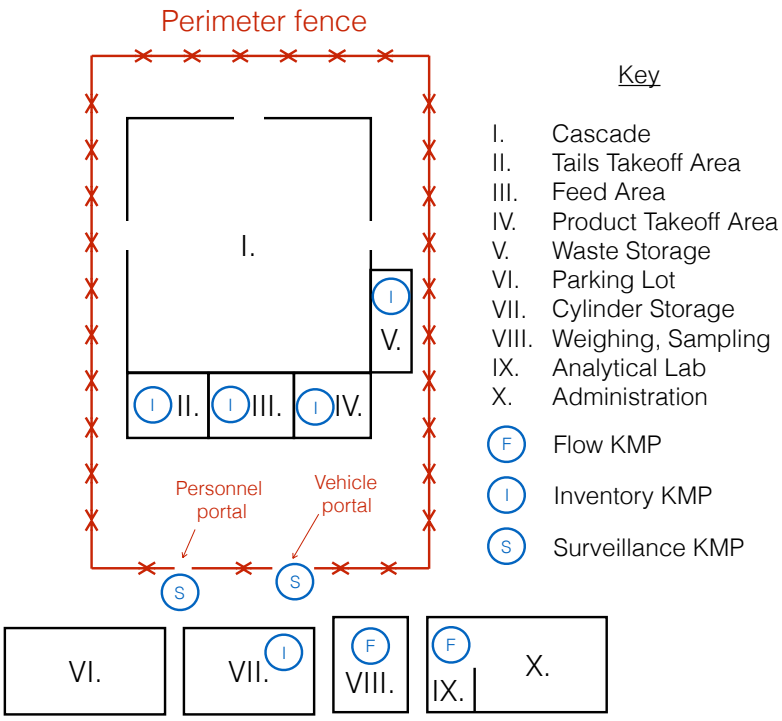

Figure 4-2: Schematic of reference GCEP in Kouts, "Reference Uranium Enrichment Plant," 1972.

[251] Herbert Kouts, "Reference Uranium Enrichment Plant," Brookhaven National Laboratory, BArch, B 196/10391 (December 6, 1972).
[252] H.D. Bengelsdorf, "Safeguarding Enrichment Plants," Draft Paper, U.S. Atomic Energy Commission, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 21, AE 13: Safeguarding Enrichment Plants, 1972 (February 14, 1972).

The primary challenge to implementing the perimeter surveillance system would be to design portal monitoring technology for the surveillance KMPs. Although radiation detector systems existed that were suitable for scanning personnel, packages, and equipment, the technology had not yet been engineered into any fieldable systems.[253] Meanwhile portal monitoring technology suitable for scanning vehicles had not yet even been shown to be feasible.[254] Detecting shielded nuclear material could be problematic – the array of six cylindrical 2"-diameter, 2" thick sodium iodide detectors conceptualized for the personnel monitor could be defeated by 2.15 kg of 93%-enriched uranium shielded in a minimum of 1/8 inch of lead,[255] which could probably be disguised in a heavy jacket. Getting around the shielding problem in the case of vehicle portal monitors[256] would be even more challenging, as vehicles could carry greater amounts of shielding. The approach proposed in the Kouts Paper featured other novel technologies (for the safeguards realm), making for fifteen in total, including an in-line enrichment meter developed by Los Alamos Scientific Laboratory, camera and TV surveillance systems, various sealing devices, as well as MIST.[257] In any case, none of these measures had ever been proposed or embraced by the Troika, and so the United States would face an uphill battle to convince the Troika that these technologies were consistent with the Parry concept.

Nevertheless, the Troika responded positively to the U.S. request, under the condition that Troika participation did not imply that a perimeter safeguards system was necessary for Almelo.[258] The

[253] Herbert Kouts, "A Perimeter Safeguards System for Enrichment Plants," Brookhaven National Laboratory, BArch, B 196/10391 (November 22, 1972), appendix B.
[254] Ibid.
[255] Ibid., Summary Sheet 2.
[256] Only passive radiation detectors were considered for this application.
[257] Ibid.
[258] Tripartite Joint Committee, "Decisions of the Joint Committee at its 6th Meeting held on 17 January at Bonn," JC/SEC/1/73, BArch, B 196/10386 (January 23, 1973), 4-5.

first meeting of the U.S.-Troika working group was held on April 26-27, 1973. In the meantime, the Troika countries had internally reviewed the Kouts papers, which they (unsurprisingly) found quite problematic. As before, the Troika States deemed the content of the Kouts perimeter safeguards paper to be in overreach of INFCIRC/153. Of the fifteen technologies proposed, the Troika was only interested in personnel doorway monitors, which complemented R&D on the same subject underway at Karlsruhe, scrap monitors, and the use of cameras at strategic points, as defined by INFCIRC/153.[259] Some of these options, including a secure central recording station and a secure crane monitor were rejected outright, and the Troika was unenthusiastic about the use of MIST as it had not yet been proven.[260] Troika personnel considered the design of the Kouts reference plant to be irrelevant, asking "Why do the Americans start from a ficticious [sic.] plant rather than picking one of the already existing plants namely one of their own?"[261,262] In particular, issue was taken with the amount of deposition assumed for the cascade traps, as well as deposition within failed machines, which the Kouts paper estimated to be an average of 103 grams *per centrifuge* after a five-year lifetime.[263] This number was likely too large given that the centrifuge rotor dimensions in the Kouts paper were 1 m in length, by 20 cm in diameter, which would likely mean that the typical gas inventory of these machines would be on the order of a few grams at most.

[259] Tripartite Safeguards Working Group, "Summary minutes of tripartite safeguards working group meeting on March 8 1973 in Bonn," BArch, B 196/10391 (March 22, 1973), annex 3, 1.
[260] Ibid., annex 3, 1–2.
[261] Ibid., 1.
[262] However, clearly the Kouts reference plant was designed to be similar in scale to the Troika's planned demonstration plants, apparently so it would be more relevant to future IAEA safeguards needs at actual facilities, as such a facility was not planned in the United States at the time.
[263] Herbert Kouts, "Reference Uranium Enrichment Plant," Brookhaven National Laboratory, BArch, B 196/10391 (December 6, 1972), 4.

The April 1973 meeting, however, went relatively smoothly. But while the two sides agreed to collaborate further at this meeting,[264] progress was lethargic. The Troika delivered official comments on the Kouts papers in June 1973,[265] but only made an offer to field test U.S. safeguards equipment in February 1974. The only technologies acceptable for field-testing at Almelo, of the devices presented in the Kouts paper, were the U.S. secure camera system, a ^{3}He passive neutron detection system, and a two-channel handheld gamma spectrometer known as the Stabilized Assay Meter (SAM-II).[266] U.S. personnel would not be granted access to Troika plants, and instead, the equipment would have to be installed and maintained by Troika personnel under the training of Americans.[267] Implementation of the field-testing, again, was slow: the test equipment would not arrive at Almelo until October 1974, and consisted only of two SAM-IIs, one prototype passive neutron enrichment meter and a single 16-mm surveillance camera system.[268] In the meantime, the U.S. had expressed disappointment to Troika representatives on the paltry array of devices that had been accepted by the Europeans for testing.[269] Under this project, the U.S. and Troika would

[264] E. Kraska, "Minutes of Tripartite Meeting with US Technical Working Group on Enrichment Plant Safeguards," BArch, B 196/10391 (May 8, 1973).
[265] D.R. Terrey, "Comments on the US Technical Working Group Proposals on Instrumentation for a Perimeter Safeguards System for Enrichment Plants," BArch, B 196/10391 (June 1, 1973).
[266] K.W. Joyner to H. Daniel Brewster, "Enrichment Safeguards," BArch, B 196/10391 (February 19, 1974), 1. For information on the SAM II, see International Atomic Energy Agency, "Application of Safeguards Procedures," *IAEA Bulletin* 19, no. 5 (October 1977): 9–13.
Joyner's letter to Brewster took particular exception to the MIST technique, stating that it would be require "substantial further development" before it could be field tested. In internal tripartite correspondence guided by UK representatives, it was noted that deviations in measured MIST results versus those expected for diffusion facilities raised doubts over the validity of the method. In addition, MIST testing would require a facility to operate at steady state for two weeks, which would cause great inconvenience to its operator. See K.W. Joyner, "US-Tripartite Collaboration on Centrifuge Plant Safeguards," BArch, B 196/10391 (December 14, 1973).
[267] K.W. Joyner to H. Daniel Brewster, "Enrichment Safeguards," BArch, B 196/10391 (February 19, 1974), 2.
[268] Leonard M. Brenner to Weller, "Loan of U.S. Safeguards Equipment," U.S. Atomic Energy Commission, PA AA, B 72 (ZA)/114144 (August 21, 1974).
[269] Tripartite Junior Joint Committee, "Minutes of a Meeting Held at Marlow on 28 June 1974," JC/SEC/74/7, BArch, B 196/10388 (June 28, 1974).

hardly move any closer in understanding on perimeter safeguards, and it seems that little work of technical value came forth from this work. After all, camera systems, handheld gamma detectors and passive neutron detectors could just as effectively be tested on UF_6 cylinders at U.S. diffusion facilities and laboratories as at an actual centrifuge enrichment facility. By March 1975, field testing of the U.S. equipment ceased, as Urenco informed the U.S. Energy Research and Development Administration, the USAEC's successor, that the equipment's import duty and value added tax exemptions would terminate the following month.[270] Before the April 1 deadline was reached, the equipment was delivered to the U.S. Embassy in Brussels.[271] This move frustrated the United States greatly, particularly as enrichment safeguards was becoming ever more relevant as negotiations advanced on a nuclear supply agreement between the FRG and Brazil in early 1975, which included provision of the German-developed jet nozzle enrichment process. In a June 1975 lunchtime conversation with a West German embassy official in Washington, Lorin Stieff, a US ACDA official,[272] tried cajoling the FRG into taking enrichment safeguards more seriously, given the possibility that it would soon become nuclear supplier itself,[273] which would come with significant responsibilities. According to the West German report of this meeting, Stieff lambasted the Troika for its halfhearted participation the U.S.-Troika technical study, lamenting that agreement could only be reached at the lowest common denominator.[274] Stieff criticized the Troika's disinterest in the project, despite the United States' open offer to supply safeguards

[270] U.S. Mission to the European Communities, EC Brussels 2655, RG 59 (AAD), *Central Foreign Policy Files 1973-1979*, (March 25, 1975).
[271] U.S. Department of State, State 66802, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (March 25, 1975).
[272] Stieff had also criticized the Troika's disinterest in safeguards technology development at a meeting with the UK in the summer of 1974. See Tripartite Junior Joint Committee, "Minutes of a Meeting Held at Marlow on 28 June 1974," JC/SEC/74/7, BArch, B 196/10388 (June 28, 1974).
[273] FRG Embassy Washington, "Technische Safeguards für Anreicherungsanlage Almelo," PA AA, B 72 (ZA)/114137 (June 3, 1975).
[274] Ibid., 1."

equipment at no cost for testing, and stated that it was a missed opportunity to set a positive precedent[275] for enrichment safeguards. Field testing of U.S. safeguards equipment at Almelo would not resume until the early 1980s.

In parallel with the quadripartite field testing of U.S. safeguards equipment, the United States also worked to keep the Troika informed of its development of MIST, in the face of Troika disinterest. In late 1973, the United States shared the results of its second MIST experiment conducted at the Oak Ridge GDP, in which the concentration of ^{234}U were measured in feed, product and tails streams during a 15-day period of steady state LEU production.[276] The observed $^{234}U/^{235}U$ ratios in the product and tails streams, however, were inconsistent with the reported flow rates in the facility, although when these flow rates were "adjusted" to match the measured product and tails enrichments, then the measured $^{234}U/^{235}U$ ratio fell within expected statistical uncertainties.[277] Sources of this error were unclear to authors of the report, who were unsure even whether the discrepancy came from cascade effects, such as non-ideality and transient concentrations across the measured cascades, to issues with the measurement devices.[278] Thus, this report did not make much of an impression on the UK government when it was presented to the UK DTI by Loren Stieff in December 1973. According to a UK DTI report of this meeting, Stieff argued that MIST

[275] In German: "Das Angebot der USA, alle Möglichkeiten einer techischen Kontrolle des Anreicherungszustandes… zu prüfen, und zwar mit kostenlos von den Amerikanern zur Verfügung gestelltem Gerät, sei von der Dreiergruppe… stets mit deutlichem Desinteresse aufgenommen worden. Die Möglichkeit eines positive Präzedenzfalles sei damals nicht genutzt worden." Ibid., 1–2."
[276] Blumkin and Von Halle, "A Preliminary Report on the Minor Isotopic Measurements; MIST Test II," K-OA-2388, Annex I in J.E. Ellingsen, "Note for the Record: Meeting to discuss the Minor Isotopes Safeguards Technique (MIST) and its application to enrichment plants held in Room 1563, Thames House South on Monday, 10 December 1972," TNA FV 70/14/24 (December 14, 1973).
[277] Ibid., 2.
[278] Ibid.

would essentially "prevent clandestine operation without recourse to intelligence activities"[279] in non-access areas of GCEPs (although in reality MIST would not detect the enrichment of undeclared material using entirely unreported enrichment capacity). UK officials, however, noted that in situations where MIST results did not match expected results, as had happened in the Oak Ridge test, a GCEP operator might be asked to provide highly detailed operating data in order to explain the discrepancy, ultimately making MIST far more intrusive than intended. It was also unclear to UK representatives at the meeting how MIST would reduce the use of any "normal" safeguards techniques for measuring material flows.[280] The use of MIST also arose in the context of safeguards for jet nozzle enrichment plants in the mid-1970s, as the FRG proposed the sale of the technology to Brazil. In April 1975, Lorin Stieff (again) had a lengthy conversation with a UK Washington Embassy official, during which he argued that MIST would be instrumental for ensuring that output from an enrichment plant was consistent with the declared feed.[281] Stieff also passed a report on the use of an on-line enrichment monitor that measured the ratio of ^{234}U to ^{235}U in liquid UF_6.[282] After reviewing the account of this conversation, however, BNFL reported that existing techniques would be suitable for safeguarding jet nozzle enrichment plants, as at other enrichment facility types, and that thus MIST was unnecessary.[283,284]

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[279] J.E. Ellingsen, "Note for the Record: Meeting to discuss the Minor Isotopes Safeguards Technique (MIST) and its application to enrichment plants held in Room 1563, Thames House South on Monday, 10 December 1972," TNA FV 70/14/24 (December 14, 1973), 1.
[280] Ibid.
[281] J. Gaunt to F. Brown, UK Embassy Washington, TNA FV 70/14 (April 16, 1975), 1.
[282] Lorin R. Stieff, Frank E. Woltz, and T.D. Reilly, "On-line Measurement of the Isotopic Composition of Uranium in UF6," attachment to ibid.
[283] H.A. Hughes to F. Brown, British Nuclear Fuels Limited, TNA FV 70/14 (April 25, 1975).
[284] In April 1976, the United States shared with the UK the results of a third MIST experiment carried out at the Oak Ridge GDP, which studied the flow of reprocessed uranium (and the ^{236}U isotope) through a cascade to measure its inventory. No documentation could be found indicating the UK government's reaction to his work. Nevertheless, there are also no indications that the UK position on MIST had changed by this time. See "MIST III Experiment," TNA FV 70/14 (April 1, 1976).

Final Thoughts

The introduction to this chapter posed the question of how the GCEP technology holders, the IAEA and Euratom managed to so deeply entrench their discord over GCEP safeguards in the early to mid-1970s. The divide between the U.S. and European GCEP safeguards visions is partly to blame. It is possible that the technical ambition inherent in the American approach had been driven by U.S. worries that the Soviet Government would criticize the IAEA's GCEP safeguards approach, if it were to rely solely on traditional safeguards measures for material accountancy verification, while totally ignoring the misuse problem. On the other hand, it may just as easily have been the case that higher funding and institutional interest in nuclear safeguards in the United States naturally led American experts to take a more unconventional approach than their Troika counterparts in proposing GCEP safeguards measures. In addition, the United States, as a Nuclear Weapon State, was not obliged to subject itself to the safeguards measures it was proposing at its own enrichment facilities. In an exchange of letters on U.S.-Troika technical cooperation, J.L.K. Thompson, of the UKDOE, wrote, "[w]e should remember that the U.S. has a large safeguards "industry" of people working full-time on safeguards instrumentation, control philosophies, rule books, etc. These people aren't interested in the ultimate financial burden on operators or countries of operating controls."[285] The U.S. approach, although inspired by good intentions, was egregiously expensive, both in terms of money and manpower. Among the Europeans, cynicism over U.S. intentions was widespread.

[285] J.L.K. Thompson to C. Herzig, annotation on note from F. Brown to C. Herzig, "Enrichment Plant Safeguards – Andrews Letter of 12 April," Attachment 1 to C. Herzig to J.L.K. Thompson, "Safeguarding Centrifuge Plants," TNA FV 70/14/29 (April 26, 1974).

The U.S. safeguards position was wholly incompatible with the Troika's GCEP safeguards concept, which had faults of its own. Perhaps the most critical oversight in the Troika view was that GCEP misuse was not a credible scenario, and that it should fall outside the purview of safeguards verification. This was wishful thinking.

The IAEA's deference to its Member States, although well intended, along with the manipulation of the IAEA's position by technology holders, also complicated future talks on GCEP safeguards. Had the IAEA been better equipped with technical expertise at the beginning, perhaps it would have questioned the Troika's assertion that misuse of a facility was unlikely (as it would do by the late 1970s), and would have pushed harder for technology holders to waive their right to exclude inspectors from cascade areas, leading to a variant of a limited cascade access safeguards approach at an earlier stage. Instead, the IAEA allowed States to delay agreement on GCEP safeguards measures for several years, ostensibly for the need to develop agreed technical measures, when in reality hardly any technical cooperation between Member States took place at all. Furthermore, the IAEA's initial, perhaps ill-informed commitment to non-access in June 1972, along with its commitment to non-access in the 1973 example Almelo FA, would become difficult to reverse in the late 1970s as evidence mounted that GCEP misuse was a credible safeguards issue, as will be discussed in the next chapter.

Euratom's GCEP safeguards conceptualization, which relied on cascade access, muddied the waters further. Not only did it set an opposing precedent to the IAEA's approach, Euratom's rationale for requiring access, as documented in Spaak's July 1972 letter, hinged on the need to verify the absence of higher-than-declared enrichment levels, undeclared capacity and nuclear

material—i.e. facility misuse—at GCEPs. The legal authority of the IAEA to verify the absence of both of these scenarios, however, was a matter of deep dispute at the time, with the FRG in particular, as well as Japan, arguing that the IAEA's safeguards mandate only extended to declared nuclear material. Had Euratom not cited the need to verify the absence of clandestine enrichment and feedstock in justifying its access approach, perhaps later discussions on IAEA cascade access would have gone more smoothly. Of course, in that case, however, no precedent for cascade access and misuse verification would have been set.

In summary, while conditions for agreeing on a GCEP safeguards approach were far from ideal when discussions began, by the mid-1970s, conditions were even worse. The common theme amidst this quagmire, from the Euratom-Troika dispute over cascade access, to the U.S.-Troika safeguards concept rift, was facility misuse. At this point, stakeholders could not even agree on whether the absence of GCEP misuse should even be verified. This fundamental disagreement made GCEP safeguards into an ever more delicate and sensitive issue as work progressed towards developing an IAEA safeguards approach. Meanwhile, international technical engagement on GCEP safeguards was both superficial and dysfunctional. Prospects for a technically grounded solution for addressing GCEP misuse grew ever dimmer.

Amidst these difficulties, in the late 1970s, as the need for an IAEA safeguards approach for Almelo became increasingly pressing, stakeholders would encounter further difficulties as the question of IAEA cascade access broke open. The following chapter discusses how this became an issue of debate.

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Chapter 5 – Coming to a Head, 1975–1980

Following a brief lull in the mid-1970s, efforts to agree to a GCEP safeguards approach gained new urgency later in the decade, following the February 1977 entry into force of the IAEA-Euratom safeguards agreement, as well as anticipation of construction of new facilities. As these new discussions took place, however, the political differences between stakeholders persisted over how to address misuse. Meanwhile, new issues of dispute, most notably the question of cascade access for verifying absence of HEU production, undeclared material and undeclared capacity under IAEA safeguards, arose. Multiple multilateral conferences on GCEP safeguards organized by the IAEA failed to make measurable progress towards resolving States' differences. By 1980, after the IAEA had convened six dedicated meetings on GCEP safeguards, and negotiations for an Almelo GCEP Facility Attachment (FA) had stretched on for three years, it was clear that a new approach was needed: intermittent conferences at the IAEA were not going to solve a problem that had proven itself to be so intractable. These conditions led to the creation of the Hexapartite Safeguards Project (HSP), a 2-year dedicated technical effort to develop an IAEA safeguards approach. HSP participants included six States that had developed or had an interest in developing GCEP technology for commercial enrichment (Australia, Japan, the Netherlands, the United Kingdom, the United States, and West Germany), and the two inspectorates tasked with performing international safeguards activities at commercial GCEPs (the IAEA and Euratom). The HSP produced a safeguards approach that addressed key elements of misuse through measures negotiated mainly via political compromise, while also addressing LEU diversion using traditional material accountancy methodology. Given the conditions that preceded it, the HSP was unable to address misuse and HEU production in a more technically motivated manner.

In the intervening time following the first multilateral discussions in the early 1970s, the IAEA took a firmer position on the necessity of cascade access to verify the absence of facility misuse, both using declared and undeclared feed and equipment. Over this period, safeguards positions of the Troika had drifted apart. While the Netherlands grew increasingly eager to conclude a facility attachment for Almelo, the FRG, with some support from the UK, used GCEP safeguards discussions as fora for arguing its position that INFCIRC/153-type safeguards were only applicable to declared material, resisting arguments in favor of cascade access that were predicated on the need to verify the absence of undeclared activities. Under these conditions, as the HSP got underway, despite intentions for it to be a technical forum, political posturing over misuse and HEU production verification were inevitable.

New GCEP Safeguards Stakeholders

For a few years in the mid-1970s, on the heels of the U.S.-Troika perimeter safeguards project, GCEP safeguards development efforts slowed somewhat, perhaps discouraged by the dismal outcome of efforts up to that point, but also for lack of immediate urgency. Although the Euratom NNWS had finally ratified the NPT together in May 1975,[1] Euratom's safeguards provisions would still need modification in order to bring terminology and practices into alignment with those specified in the IAEA-Euratom agreement, prior to entry into force of the IAEA-Euratom agreement. To this end, a new, more detailed Euratom Commission regulation, No. 3227/76, was

[1] United Nations Office of Disarmament Affairs, "Treaty on the Non-proliferation of Nuclear Weapons: Status of the Treaty," accessed June 22, 2017, http://disarmament.un.org/treaties/t/npt.

enacted in October 1976, superseding Regulations 7 and 8.[2] As this work was taking place, U.S.-Troika GCEP safeguards collaboration diminished. Development of a FA for Almelo would only become pressing after the entry into force of the IAEA-Euratom agreement in 1977. This is not to say, however, that GCEP safeguards issues fell off the map completely during this period.

Japanese development of centrifuge technology advanced substantially through the 1970s. After the Japanese government boosted resources devoted to centrifuge development early in the decade, a 180-machine pilot cascade was operational by the fall of 1974, and a second 247-machine cascade went into operation in the summer of 1976.[3] Following success in operating the second cascade,[4] plans were put in place to construct a pilot plant, to be completed in early 1980s. Japan's status as an NPT party, along with its comprehensive safeguards agreement, which entered into force in December 1977, meant that its centrifuge enrichment facilities would be subject to IAEA safeguards. The nominal capacity of the Japan's pilot plant, located at Ningyo Toge, was 36 tSWU/a, with a designated maximum product enrichment of 3.2%.[5] Although FA negotiations for

[2] This new regulation went beyond the provisions for design information and material declarations laid out in Regulations 7 and 8, to cover new obligations for States under the IAEA-Euratom agreement (INFCIRC/193). Regulation 3227/76 requires States to report imports and exports of nuclear material to Euratom, for example, as Euratom is obligated to report these activities under Articles 12, and Articles 91-94 of the agreement. Terminology used by the IAEA in the model comprehensive safeguards agreement, such as 'inventory change report,' 'material balance report,' and 'physical inventory listing,' is used in the new Euratom regulation. See "Euratom Regulation 3227/76," *Official Journal of the European Union* L 363 (1976): 1–57; "The Text of the Agreement Between Belgium, Denmark, The Federal Republic of Germany, Ireland, Italy, Luxembourg, The Netherlands, The European Atomic Energy Community and the Agency in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons," INFCIRC/193, (Vienna: International Atomic Energy Agency, September 14, 1973).
[3] U.S. Embassy Tokyo, Tokyo 1285, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (January 28, 1977).
[4] R. Scott Kemp, "*Nonproliferation Strategy in the Centrifuge Age*," (PhD diss., Princeton University, June 2010), 65.
[5] U.S. Embassy Tokyo, Tokyo 3976, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (March 7, 1979).

the Ningyo Toge plant were underway in early 1979,[6] by the time the facility began producing enriched material in September 1979, no agreement had been reached on a safeguards approach for the plant, due to Japanese opposition to inspector cascade access, in step with Troika concerns.[7]

While U.S.-Troika collaboration diminished, the United States made efforts to engage with South Africa over enrichment safeguards. Although South Africa's enrichment efforts, which were disclosed by Prime Minister B.J. Vorster during a parliamentary no-confidence debate in July 1970,[8] are now known to have been directly tied to nuclear weapons production,[9] the United States made diplomatic overtures to convince South Africa to join the NPT. In the course of these discussions, the South African government insisted (perhaps in bad faith, knowing that enrichment safeguards were an intractable issue) that IAEA inspection requirements and procedures for uranium enrichment plants be specified before South Africa would consider signing the NPT.[10] South Africa used a unique method for enriching uranium, relying passage of UF_6 mixed with hydrogen through a vortex tube, and was highly secretive about technical details of the process, not even publicly disclosing the fact that it used aerodynamic principles until 1975.[11]

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[6] Ibid.
[7] U.S. Embassy Vienna, Vienna 9249, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (August 31, 1979); Embassy Tokyo, Tokyo 22530, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (December 27, 1979).
[8] U.S. Consulate Cape Town, Cape Town 826, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 12, DEF 18-6 NPT [Nuclear Nonproliferation Treaty], 1970 (July 23, 1970).
[9] See, for example, Jeffrey T. Richelson, *Spying on the Bomb: American Nuclear Intelligence from Nazi Germany to Iran and North Korea* (New York: W.W. Norton & Co., 2007), 368–380.
[10] U.S. Embassy Pretoria, Pretoria 3248, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (August 27, 1975).
[11] A.J.A. Roux et al., "Development and progress of the South African Enrichment Project," in *Proceedings of the International Conference on Nuclear Power and its Fuel Cycles*, IAEA-CN-36/300 (Salzburg: International Atomic Energy Agency, May 2–13, 1977).

In assessing the South African NPT position in 1975, the U.S. Department of State perceived that South Africa was concerned about inspector access to sensitive technology, and discussed internally how reassurances could be made that IAEA inspectors would not access areas of facilities that housed items such as separation equipment.[12] At the time, the IAEA was still committed to the application on non-access areas in enrichment plants, as it had been since the 1972 Technical Working Group meeting. Officials at the U.S. Mission to the IAEA noted that the example Almelo FA,[13] prepared in 1973 to allow for the signing of the IAEA-Euratom agreement, explicitly acknowledged that IAEA inspectors could be excluded from parts of facilities. Additionally, the U.S. Mission recalled that IAEA had produced a draft paper for a Consultants' Meeting on enrichment safeguards in 1974, which was to be incorporated into the Safeguards Technical Manual (STM), a highly detailed document listing specific practices and techniques to be employed in the IAEA's implementation of IAEA safeguards.[14] This paper also explicitly stated that inspector access could be limited, although this would come at the expense of "increased use of surveillance measures" (this point was clearly influenced by the U.S. GCEP safeguards philosophy).[15] Although neither document was public at the time, a precedent for non-access had

[12] U.S. Mission to the IAEA, IAEA Vienna 7658, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (September 8, 1975).
[13] Ibid., 2–3; Commission of the European Communities, "Mitteilung der Kommission und Entwurf eines Beschlusses des Rates zur Billigung der "ergänzenden Abmachungen" des Übereinkommens zwischen dem Königreich Belgien, der Bundesrepublik Deutschland, der Italienischen Republik, dem Großherzogtum Luxemburg, dem Königreich der Niederlande, der Europäischen Atomgemeinschaft und der Internationalen Atomenergie-Organisation in Ausführung von Artikel III, Absätze 1 und 4 des Vertrages über die Nichtverbreitung von Kernwaffen," Attachment 1, KOM(73) 363 (final version), PA AA, B 72 (ZA)/114137 (March 14, 1973).
[14] Stieff Research and Development Co., Inc., "The International Atomic Energy Agency and International Safeguards," Appendix IX-C in *Nuclear Proliferation and Safeguards: Appendix Volume II Part Two,* (Washington: U.S. Office of Technology Assessment, 1977), IX-45.
[15] U.S. Mission to the IAEA, IAEA Vienna 7658, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (September 8, 1975). The 1974 Consultants' Meeting paper prepared by the IAEA likely became Chapter 2 of the Safeguards Technical Manual, Part C. A 1976 draft of this chapter begins with the sentence, "The specification of inspection procedures for uranium enrichment facilities is complicated by the fact that at least some facility operators may be expected to request that inspector access to a portion of their process

effectively been set, and the United States considered sharing both the Almelo example FA and the draft STM chapter with the South African government, along with assuring the South African government that the United States would lobby the IAEA to ensure that non-access requests were upheld.[16]

The South African government, in the midst of pursuing a nuclear weapons program at the time, nevertheless chose not to sign the NPT. This episode, despite it concerning a different enrichment technology than centrifugation, illustrates where the accepted line of thinking vis-à-vis cascade access lay during the mid-1970s, as well as some additional motivation for why the non-access approach was supported in early GCEP safeguards discussions. It may have been that South Africa's security concerns may have been a bluff to give its government an excuse not to sign the NPT, but these concerns, as perceived by other States, could have been used to motivate the exclusion of inspectors from sensitive facility areas, in the name of getting broader NPT acceptance.

During this 'less active' period, safeguards at Urenco's Capenhurst GCEP in the United Kingdom came into consideration. As discussed in the previous chapter, the question of Euratom inspector access rights at Capenhurst arose in 1975-76, with the UK Government, unlike that of Netherlands, choosing to resist Euratom access to cascade areas. Although the UK was open to granting 'limited' access to EURATOM, in which cascade hall inspections would be curtailed to minimize

not be permitted." See International Atomic Energy Agency, "Chapter 2: Uranium Enrichment Facilities," *Safeguards Technical Manual, Part C*, Draft, TNA FV 70/14 (1976).

[16] U.S. Mission to the IAEA, IAEA Vienna 7658 (September 8, 1975).

inconvenience to operations and mitigate security risks,[17] EURATOM insisted on maintaining its full statutory access rights (i.e. unlimited access contingent upon its necessity for safeguards verification).[18] After the conclusion of the UK's Voluntary Offer Agreement (VOA), made in September 1976 between the UK, the IAEA and Euratom, it also became apparent that Capenhurst, as a civil nuclear facility, would be subject to IAEA safeguards under this agreement. Article 1(a) of the UK VOA (INFCIRC/263) requires all nuclear material and in civil activities in the UK to be offered for safeguards, including all material at the Capenhurst GCEP.[19] By way of the October 1978 entry into force of the UK VOA, IAEA safeguards at Capenhurst became relevant, although the IAEA did not select the Capenhurst GCEP for safeguards in the years leading up to the HSP.

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[17] Fred Brown to Peter Irwin, "Access to Centrifuge Enrichment Facilities," UK National Archives (TNA) FV 70/17/1 (March 15, 1976).

[18] Fred Brown to Peter Kelly, "The Hexapartite Safeguards Project (HSP): Tokyo Meetings 4-13 November 1981," TNA FCO 96/1465/91 (November 19, 1981).

[19] The text of Article 1(a) reads:

"The United Kingdom shall accept the application of safeguards, in accordance with the terms of this Agreement, on all source or special fissionable material in facilities or parts thereof within the United Kingdom, subject to exclusions for national security reasons only, with a view to enabling the Agency to verify that such material is not, except as provided for in this Agreement, withdrawn from civil activities." See "The Text of the Agreement of 6 September 1976 between the United Kingdom of Great Britain and Northern Ireland, the European Atomic Energy Community and the Agency in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons," INFCIRC/263 (Vienna: International Atomic Energy Agency, October 1978).

Note that the analogous clause in the U.S. VOA (INFCIRC/288) is worded slightly differently, so as to not encompass all material in civil uses with exceptions for national security as the UK VOA does, but instead to exclude safeguards at facilities that have national security significance while not explicitly covering all material in civil use. Thus, while the UK VOA language clearly prescribes that Capenhurst be offered for safeguards, the U.S. VOA is less explicit about offering a civil GCEP for safeguards. Article 1(a) of the U.S. VOA reads:

"The United States undertakes to permit the Agency to apply safeguards, in accordance with the terms of this Agreement, on all source or special fissionable material in all facilities within the United States, excluding only those facilities associated with activities with direct national security significance to the United States, with a view to enabling the Agency to verify that such material is not withdrawn, except as provided for in this Agreement, from activities in facilities while such material is being safeguarded under this Agreement."

In late 1976, plans were put in place to construct a 1000 tSWU/a-scale GCEP in West Germany, to go into operation in 1985. Although Urenco's managing board had agreed to complete 600 tSWU/a of capacity at Almelo before building a German plant[20] (and planned capacity at the time at Almelo would only reach 200 tSWU/a by 1978, following completion of the SP3 demonstration plant), the German Urenco shareholder, Uranit, was concerned that the necessary capacity expansion at Almelo would not go ahead.[21] The Tripartite JC would not take steps towards approving the new German plant until April 1978,[22] after the Dutch Second Chamber had approved expansion of Almelo (following a ten-month delay),[23] the selection of a site in the town of Gronau the month prior,[24] as well as threats from the FRG that it would withdraw from the Treaty of Almelo after its initial ten-year term if the facility was not approved.[25] As plans for a new German facility moved towards fruition, the FRG's stake in GCEP safeguards development became more important.

[20] R.B. Kehoe, *The Enriching Troika: A History of Urenco to the Year 2000* (Marlow, UK: Urenco Limited, 2002), 97.
[21] U.S. Embassy Bonn, Bonn 21069, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (December 15, 1976).
[22] Kehoe, *The Enriching Troika*, 97.
[23] A Dutch parliamentary decision for expanding Almelo (i.e. building SP4) had originally been planned to be made by April 1, 1977. However, expansion of the plant served towards fulfilling a supply agreement to provide enriched uranium to Brazil, negotiated by the FRG. As Brazil was a non-NPT party at the time, Dutch politicians were concerned about the safeguards measures that would be applied the enriched material, as well as the resulting spent fuel (and contained plutonium). Given the apparent political implications of expanding Almelo, this decision was delayed until after the Dutch general elections, held on May 25, 1977. However, 208 days passed between the election and formation of a new coalition government, and a decision on Almelo was delayed until February 1978. See U.S. Embassy The Hague, The Hague 1033, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (February 25, 1977); U.S. Embassy The Hague, The Hague 605, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (February 6, 1978).
[24] Ritter to Landesanstalt für Wasser und Abfall, "Genehmigungsverfahren nach § 7 Atomgesetz; Urananreicherungsanlage 1000 t UTA/a in Gronau," BArch, B 196/69210 (March 21, 1978).
[25] U.S. Embassy The Hague, The Hague 7240, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (December 29, 1978).

The United States also took steps towards commercializing GCEP technology in the mid-1970s. At the time, demand for nuclear energy was expected to grow substantially, and nuclear power development programs had been accelerated in the wake of the 1973 OPEC oil embargo. A commensurate growth in global enrichment capacity was needed. By late June 1974, projected demand had risen so high that the U.S. Atomic Energy Commission (USAEC), which operated all U.S. enrichment facilities at the time, suspended all enrichment contracting, for lack of available capacity.[26] Although the USAEC resumed contracting one month later, accompanied by a statement by President Nixon encouraging the development of privately owned enrichment facilities,[27] this incident nevertheless harmed global confidence in the U.S. enrichment supply.[28] European utility companies increasingly turned to Soviet enrichment suppliers.[29] By the fall of 1975, Union Carbide, which provided technical management for the U.S. government's enrichment program, was advocating for the construction of two 8800 tSWU/a GCEPs—one in Portsmouth, Ohio and the other in Oak Ridge, Tennessee, to shore up the U.S. enrichment supply.[30] Two years later, an official announcement was made on construction of the planned GCEP at Portsmouth, Ohio,[31] bringing the United States into the club of countries pursuing

[26] U.S. Department of State, State 152033, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (July 15, 1974); Felix Obussier, "Statement by Felix Oboussier, Director General of the Euratom Supply Agency of the European Communities at the Hearings on Uranium Enrichment," Joint Committee on Atomic Energy of the U.S. Congress (July 16, 1974), http://aei.pitt.edu/12991/1/12991.pdf.
[27] U.S. Department of State, State 169744, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 37, FSE 15: AEC Uranium Enrichment Contracting, 1974 (August 4, 1974).
[28] See, for example, U.S. Embassy Bonn, Bonn 12678, RG 84, *Classified and Unclassified Subject Files 1959-1976*, Box 37, FSE 15: AEC Uranium Enrichment Contracting, 1974 (August 12, 1974).
[29] William M. Drozdiak, "Europeans Turning to Soviet Uranium," *The New York Times*, July 6, 1975, http://www.nytimes.com/1975/07/06/archives/europeans-turning-to-soviet-uranium.html.
[30] Glenn Schleede to Jim Cannon, "Meeting with Dr. Seemans on Uranium Enrichment," Memorandum, Box 36, James M. Cannon Files, Gerald R. Ford Presidential Library (September 8, 1975), https://www.fordlibrarymuseum.gov/library/document/0039/16989366.pdf.
[31] "Carter Wants New Nuclear Fuel Plant," *The Washington Post,* July 12, 1977, https://www.washingtonpost.com/archive/politics/1977/07/12/carter-wants-new-nuclear-fuel-plant/2b091091-fcec-4d39-8f53-49def6392a0c/?utm_term=.c58406ce30c8.

commercialization of centrifuge enrichment technology. Under the U.S. VOA, agreed in November 1977, there existed a possibility that this facility could be offered for IAEA safeguards.[32]

Nevertheless, in early 1977, as the IAEA-Euratom safeguards agreement went into force, the Almelo GCEP was, however, the only operational GCEP that was subject to safeguards under an active safeguards agreement. At this point, agreement of an IAEA-Euratom Almelo FA became a pressing legal requirement. Given this necessity, multilateral discussions on enrichment safeguards resumed, beginning with an IAEA Advisory Group meeting convened in Tokyo in March 1977.

The Tokyo Advisory Group Meeting, 1977

Immediately prior to the Tokyo Advisory Group meeting, topics of disagreement over GCEP safeguards had not changed much from the first IAEA Technical Working Group in 1972 (and from a less consequential Consultants' Meeting held in 1974). Agreement on verification measures for GCEP misuse was still elusive. As is evident from a briefing cable sent by the U.S. Mission to the IAEA, the United States and the Troika still disagreed over whether paragraph 76(d) of INFCIRC/153 could be invoked if inspectors were excluded from cascade halls, to authorize additional inspection effort. The question of MRIE calculation formulae (paragraph 80(b) or 80(c)) was unresolved, and the United States still supported use of the Minor Isotope Safeguards Technique (MIST), despite little enthusiasm for the method from other States.[33] In closing, the

[32] See footnote 19 for a discussion on differences in language between the U.S. and UK VOAs, and the applicability of this difference to safeguards at GCEPs.
[33] U.S. Mission to the IAEA, IAEA Vienna 1115, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (February 11, 1977).

U.S. Mission recommended that the U.S. delegation be prepared to engage in discussions on both technical and political levels, considering the disagreements that had transpired beforehand in similar fora.

The IAEA, as it had done in 1972, prepared a paper in advance of the meeting. Like STR-14, the new paper, eventually published in September 1977 as IAEA-AG-110,[34] considered safeguards applied all types of enrichment facilities under consideration or operation at the time, including plants that used gaseous diffusion, gas centrifuge, the German Becker nozzle process, as well as the South African vortex method. The Tokyo meeting, however, focused on centrifuge safeguards, which presented the primary problem. Unlike STR-14, which merely considered facility characteristics and safeguards techniques to be applied at enrichment facilities, however, the new paper contained an explicit analysis of diversion pathways, followed by a generic safeguards strategy for a centrifuge enrichment plant, based on the layout of a Urenco plant. At the highest level, diversion scenarios were divided into two categories: diversion of declared material existing in a facility (without any further enrichment), and use of equipment to produce uranium enriched to levels higher than declared, and then subsequent diversion of the material. A diagram used to illustrate the two diversion strategies in IAEA-AG-110 is given in Figure 5-1.

[34] International Atomic Energy Agency, "Safeguarding Uranium Enrichment Facilities: Review and Analysis of the Status of Safeguards Technology for Uranium Enrichment Facilities," IAEA-AG-110 (Vienna, September 1977).

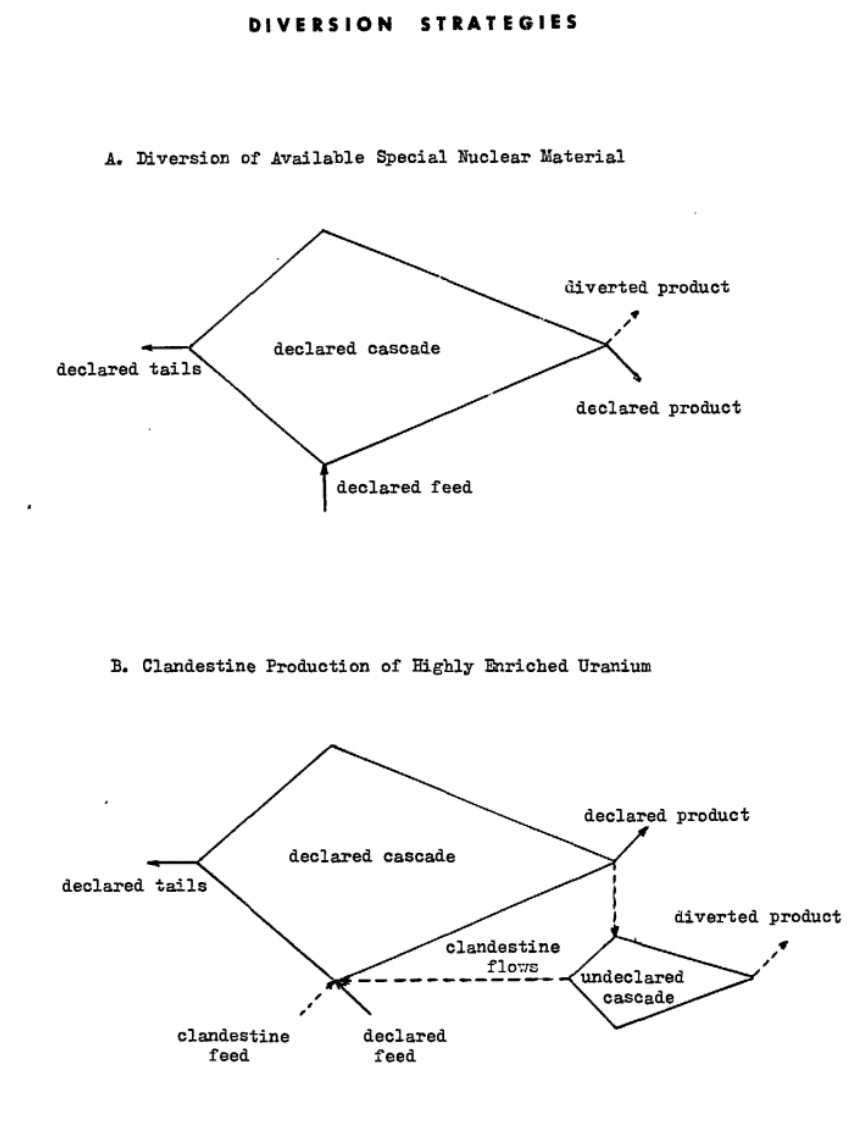

Figure 5-1: Diversion strategies, as presented in IAEA-AG-110. Source: International Atomic Energy Agency, "Safeguarding Uranium Enrichment Facilities: Review and Analysis of the Status of Safeguards Technology for Uranium Enrichment Facilities," IAEA-AG-110 (Vienna, September 1977).

From Figure 5-1, it is obvious that the IAEA considered the possible existence of undeclared feed and undeclared capacity as a credible scenario. Regarding undeclared feed, the paper argued that because safeguards began (at the time) at the point UF_6 left a conversion facility, it would be possible for undeclared natural UF_6 to be produced at a conversion plant.[35] In the meantime, IAEA-

[35] Ibid., 47–48.

AG-110 noted that producing a significant quantity (SQ) of 90%-enriched material using an undeclared cascade within a period of one year, using diverted product material, would require an undeclared capacity of as little as 1.6 tSWU/a,[36] on the order of a thousandth of a commercial facility's capacity. But while the question of the applicability of dealing with undeclared feed and capacity under INFCIRC/153-type safeguards would become a major issue later on, during the HSP, delegates at the Tokyo meeting agreed that misuse involving these elements was possible. Annex A of IAEA-AG-110, which contains the conclusions and recommendations of the Advisory Group, states that misuse "might or might not be accompanied by the introduction of undeclared feed material."[37]'

In line with precedent since the 1972 Technical Working Group meeting, IAEA-AG-110 recognized that inspector access to certain areas of plants could be restricted under Article 46(b)(iv) of INFCIRC/153, but that all personnel and equipment access points to the non-access area would need to be sealed or under surveillance.[38] While this position more closely reflected the U.S. perimeter safeguards proposal, and less the input-output system devoid of surveillance presented in the Troika's Parry Paper, this position was not unacceptable to the Troika. IAEA-AG-110 was vague about the inspection effort required for undertaking C/S around special MBAs, stating that the required amount of effort was "not completely clear."[39] This assessment did not endorse any of the measures proposed by the United States for implementing perimeter safeguards. No prescription was made about whether a continuous inspector presence was needed: the Advisory Group only agreed that "routine inspector access" to the boundaries of special MBAs

[36] Ibid., 16.
[37] Ibid., Annex A, 1.
[38] Ibid., 25.
[39] Ibid.

would be required.[40] In any case, up to this point, the Troika had never articulated a position on C/S around a closed MBA, besides its opposition to measures that would exceed INFCIRC/153 paragraph 80(c) inspection effort. Thus, the language in IAEA-AG-110 was acceptable. Because the question of inspection effort remained, however, the group agreed that case studies be undertaken to determine the actual amount needed, while recognizing that some States (most likely the United States) might be willing to accept continuous inspection, or inspection effort exceeding levels given in INFCIRC/153.[41]

The Tokyo meeting was intended to establish an agreed basis for GCEP safeguards measures, including those to be applied at Almelo, and it appears, at first glance, that it succeeded. A consensus document, with both U.S. and Troika approval, was produced. The path forward seemed clear-cut. The non-access principle would be upheld, leaving C/S measures at boundary areas as the only major issue to be resolved. In retrospect, however, the disagreement that had riddled earlier GCEP safeguards talks persisted. The question of the applicability of undeclared activities, which was central to the determining appropriate C/S measures, went unaddressed. If undeclared feed was not to be considered a credible problem, C/S measures at special MBA boundaries would need to be far less robust, as diversions from the known input of the plant could be detected via material accountancy. But even more significantly, the results of this meeting would sow a fundamental misunderstanding between the IAEA and States on the issue of non-access areas. Within one year, the consensus built around non-access to cascade areas, seemingly agreed at the Tokyo meeting, would disappear entirely.

[40] Ibid., Annex A, 2.
[41] Ibid., Annex A, 3.

"Common Perception of Ground Rules Has Been Lost"

Work on the Almelo FA got underway shortly after the Tokyo Advisory Group meeting, with the Troika assuming that the non-access model would serve as the basis for inspection activities. As negotiations progressed, however, and as the IAEA gained familiarity with the Almelo site, the IAEA began to push for access to cascade areas, effectively placing instead the border of the non-access MBA at the outer casings of centrifuges. This change in tack, against the precedent that had been set for more than half a decade, ground progress towards the Almelo FA to a halt. In the meantime, rifts in GCEP safeguards policy among Troika States emerged in the late 1970s, particularly between the Netherlands on one side and the FRG and UK on the other. While the Netherlands increasingly sought the expedient conclusion of a safeguards strategy for Almelo, regardless of its access provisions, for the sake of maintaining its strong nonproliferation credentials, the FRG and UK prioritized winning the fight with the inspectorates over cascade access. Thus, by the time discord between the Troika and IAEA became so entrenched that it necessitated the creation of the HSP, GCEP safeguards preferences also diverged within the Troika itself, leading to yet an additional obstacle to a successful outcome.

On the heels of the Tokyo meeting, the Troika understood that use of special MBAs was the agreed path forward. In June 1977, Euratom,[42] on behalf of the Dutch government, requested that the special MBA provision be applied to cascade halls at Almelo. The text of the request, signed by H.W. Schleicher, Director of the Euratom Safeguards Directorate, read:

[42] Pursuant to the IAEA-Euratom agreement (INFCIRC/193), Euratom negotiates facility attachments with the IAEA, on behalf of its Member States, instead of organizations within States themselves, as is done under most other IAEA safeguards agreements.

> "I am written [sic.] to inform you that at the request of the Netherlands government the cascade-halls of the enrichment facility of Urence [sic.] Nederland Operations B.V.… are to be considered as a process step involving commercially sensitive information pursuant to Article 46(b)(iii)[43] of the agreement."[44]

At this stage, however, the IAEA had not yet received design information for the facility. As discussed in the previous chapter, designation of special MBAs, under INFCIRC/153 safeguards, is to be considered during review of design information. Rudolf Rometsch, now titled Deputy Director General (DDG) for Safeguards at the IAEA, responded to this effect to Schleicher, sending a reminder that design information for Almelo had not been transmitted, and that the request would only be considered during the IAEA's examination of the design information.[45]

When the time came for the IAEA to review design information for Almelo, the situation began to unravel. The IAEA, now equipped with technical knowledge of the plant's design, became far more aggressive in pursuing cascade access. Upon performing Design Information Verification (DIV) at Almelo in January 1978, IAEA inspectors requested access to cascade areas, to investigate how containment measures could be set up at cascade boundaries. The plant operator, however, denied the request, echoing the Troika line that cascade hall access was not "needed."[46] In response, the IAEA produced a position paper in March 1978, which argued that the special MBA provision that appeared in the 1973 example Almelo FA (and in the results of the 1977

[43] Owing to slight differences between the model CSA and the IAEA-Euratom agreement, INFCIRC/153 paragraph 46(b)(iv) appears in the IAEA-Euratom Agreement (INFCIRC/193) as Article 46(b)(iii).
[44] "Schreiben Schleicher an Rometsch vom 8.6.1977" (June 8, 1977), attachment 2 to FRG Wien Inter to Bonn Auswärtiges Amt, Telegram No. 146, PA AA, B 72 (ZA)/123659 (March 23, 1978).
[45] "Schreiben Rometsch an Schleicher vom 24.6.1977," (June 24, 1977), attachment 3 to FRG Wien Inter to Bonn Auswärtiges Amt, Telegram No. 146, PA AA, B 72 (ZA)/123659 (March 23, 1978).
[46] "IAEO-Positionspapier vom 21.3.1978," (March 21, 1978), attachment 1 to FRG Wien Inter to Bonn Auswärtiges Amt, Telegram No. 146, PA AA, B 72 (ZA)/123659 (March 23, 1978).

Tokyo Meeting) only applied to routine inspection activities, and did not apply in the context of DIV, whose legal authority is separate from that for routine inspections, under comprehensive safeguards agreements (CSAs). The position paper went as far as to argue that "the Agency must also be able to assure itself on a continuous basis of the intefrity [sic.] of the containment," and in doing so, would need to access piping and connections inside the cascade area[47] during subsequent DIV activities. Furthermore, the position paper noted that the IAEA-Euratom agreement does not differentiate between access rights for IAEA and Euratom inspectors,[48] invoking the precedent of unlimited inspector access under Euratom safeguards that had been in place since 1973. In sum, the IAEA's request for cascade access, although it was technically consistent with past agreements on inspector access provisions (none of which addressed access during DIV), embodied a distinct break with precedent.

In March 1978, two days after the IAEA's position paper had been transmitted to the Troika, the IAEA arranged a meeting with representatives from the three States, who voiced their opposition to the IAEA's proposal. Recognizing that the special MBA issue had far-reaching political implications, the parties agreed to set aside the question in the Almelo FA negotiations for the time being, and the IAEA undertook to discuss the issue with other technology holders.[49]

Agreeing on a safeguards approach for Almelo was still an urgent task. In spring 1978, fears still existed that the absence of IAEA safeguards at Almelo could be used politically by the Soviet

[47] Ibid.
[48] Ibid.
[49] FRG Wien Inter to Bonn Auswärtiges Amt, Telegram No. 146, PA AA, B 72 (ZA)/123659 (March 23, 1978).

Union to embarrass the Troika in the IAEA Board of Governors (BoG).[50] Thus, hoping to convince the IAEA to embrace non-access once again (this time, including during DIV), the Troika conceded, via letters to the IAEA Director General and Euratom Safeguards Directorate, its willingness to consider inspection effort levels higher than those given in paragraph 80 of INFCIRC/153, in exchange for exclusion of inspectors from cascades. The lengths to which the Troika countries were willing to go, however, differed: while the Dutch government's draft of the letter offered the IAEA continuous inspector presence,[51] the FRG government opposed this.[52] The final draft of the Troika's letter referenced the conclusions of the Tokyo Meeting, which upheld non-access, and also acknowledged that some States, including the Troika members, would consider waiving the MRIE limit in INFCIRC/153.[53] To convince the IAEA that existing containment measures at Almelo were sufficient for establishing a non-access area, the Troika invited the IAEA Secretariat, along with Euratom, to visit Almelo to better understand how C/S could be deployed at the boundaries of special MBAs.[54] Both parties accepted the invitation.

This visit, which took place on July 4-5, 1978, worsened the divide between the IAEA and the Troika. Both inspectorates sent high-level delegates: the IAEA team was led by DDG Rometsch, who was accompanied by Hans Grümm, who would take over his position that September, and Euratom was represented (albeit rather passively) by Schleicher. After a tour of the 200 tSWU/a

[50] Ibid.
[51] Vincent J.J.M. Bruys to F. Brown et al., "Conslusions [sic.] of Meeting of Tripartite Asafeguards-experts [sic.] on Inspection of the Almelo Enrichment Plant," PA AA, B 72 (ZA)/123660/491.23/SB3 (May 3, 1978).
[52] The copy of the Dutch draft offer letter obtained at the Political Archives of the German Foreign Office brackets out the offer to place Almelo under continuous inspection. See "Draft-letter to be Sent by Secretary of the Joint Committee to IAEA and to European Commission," Attachment to ibid., 3.
[53] A.J. van Galen Last to Sigvard Eklund, "Almelo Enrichment Plant," JCM 4/78, PA AA, B 72 (ZA)/123660/491.23/SB3 (May 22, 1978).
[54] Ibid.

SP3 demonstration plant, which did not feature entry into the cascade area, Rometsch clarified the IAEA's position further. Although he believed that access inside individual centrifuges was undesirable, as this would contravene classification policy, as well as be harmful to nonproliferation efforts, Rometsch emphasized the need to verify the absence of HEU production in cascade halls. Verifying cascade piping configurations, as well as the absence of clandestine operations at potential feed and withdrawal points within the cascade hall, was essential to achieving this objective. Thus, Rometsch argued that the boundaries of the non-access area would have to lie within the cascade halls. While he nevertheless offered to implement safeguards on an ad-hoc basis outside the cascade halls using C/S measures to verify flows in and out of the closed areas, Rometsch warned that doing so would be time-intensive, expensive, and could potentially be unacceptable to the IAEA Board of Governors.[55]

In taking this position, the IAEA was now not only advocating for cascade access during DIV, but also during routine inspection activities. Although it could still be argued that the IAEA was nominally upholding the special MBA concept, by drawing the borders of the special MBA at the outer casings of centrifuges, from the perspective of the Troika, the IAEA's position had completely departed from the understanding reached at the Tokyo meeting a year earlier.

Why did the IAEA's position change so dramatically? It may have been the case that Rometsch, considering his legacy during his final months as DDG, sought to take a more aggressive stance against the Troika, after he had been criticized for bending too often to the demands of Member

[55] "Sicherungsmaßnahmen für Urenco-Anreicherungsanlage Almelo; Expertengespräch Urenco/IAEO/Euratom am 4./5.7.1978," PA AA, B 72 (ZA)/123660/491.23/SB3 (July 7, 1978).

States.[56] Another plausible explanation, however, is that upon reviewing design information for Almelo for the first time, the IAEA realized the necessity of cascade access for verifying the absence of HEU production. With the cascade area closed to inspectors (and without perimeter surveillance around it that would in any case be overly expensive), it would be too easy for an operator to secretly introduce undeclared material to the cascade hall, enrich it to weapons levels, extract it, and remove it from the facility. In a meeting with U.S. officials later that month, Rometsch mentioned that he saw two large doors leading to the SP3 cascade area during the Almelo tour, "through which trucks, sufficiently large to carry a 5-ton cylinder of UF_6, for example, could enter or depart."[57] Minutes of the meeting taken by the IAEA state that during the tour, a truck was seen leaving the SP3 building, carrying a "closed metallic container," 60 m^3 in volume (presumably a standard semi-truck).[58] Prior to Almelo DIV activities in 1978, the IAEA had no on-the-ground experience evaluating safeguards-relevant characteristics of enrichment facilities, instead relying on Member State advice to form its position on GCEP safeguards. Upon assessing the facts, the IAEA came to a very different conclusion about access—but at this stage, unfortunately, the IAEA would not only have to argue its case, but it would also have to undo the precedent to which it had previously committed when it had been less informed about the technical characteristics of Almelo.

[56] See Slobodan Nakićenović to Rudolf Rometsch, "Instructions and Guidelines Regarding Organization of Safeguards Work," Interoffice Memorandum, International Atomic Energy Agency, PA AA B 72 (ZA)/119530 (July 30, 1976).
[57] U.S. Embassy Vienna, Vienna 6337, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (July 13, 1978).
[58] R. Rometsch, "Visit to Almelo on 4 and 5 July 1978," (July 12, 1978), attachment to A.J. von Galen Last to M. van Hees, "IAEA report on the safeguards meeting at Almelo, 4-5 July, 1978," JCM 6/78, PA AA, B 72 (ZA)/123660/491.23/SB1 (September 12, 1978).

The IAEA position on cascade access, however, was not the only position evolving at the time, however. As the Troika, as a whole, resisted the IAEA's about-face, Dutch government officials became increasingly sympathetic to permitting cascade access. An FRG memorandum of the July 1978 Almelo meeting notes that in preparing for the meeting, some members of the Dutch delegation supported giving access to IAEA inspectors, along the same lines of unrestricted access provisions that had given to Euratom inspectors,[59] five years earlier, against the will of the UK and FRG. The Netherlands, as the only State with an operating GCEP required to be subject to IAEA safeguards, and with a government especially sensitive to domestic and international perceptions of its nonproliferation credentials,[60] was likely under greater pressure than its partners to conclude an Almelo FA quickly. Abiding by the will of the IAEA would certainly expedite this process. Also, from a Dutch perspective, the presence of IAEA inspectors in cascade halls, apart from inspectors being of different nationalities, would not represent a great departure from the status quo. The UK and FRG strongly resisted this stance. The UK, still in the process of negotiating Euratom safeguards measures for Capenhurst, strongly opposed the application of unlimited inspector access, and had been hoping that an agreement to restrict IAEA access would in turn demonstrate that Euratom had no justification to pursue unlimited access at Capenhurst.[61] The FRG, especially towards the late 1970s and early 1980s, would take a more political stance, arguing that the IAEA was basing its demands for access on misuse scenarios that lay outside the scope of INFCIRC/153-type safeguards in NPT Non-Nuclear Weapon States (NNWS), and that cascade access was therefore unnecessary.

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[59] "Sicherungsmaßnahmen für Urenco-Anreicherungsanlage Almelo; Expertengespräch Urenco/IAEO/Euratom am 4./5.7.1978," PA AA, B 72 (ZA)/123660/491.23/SB3 (July 7, 1978), 4.
[60] U.S. Embassy The Hague, The Hague 422, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (January 23, 1979).
[61] "Sicherungsmaßnahmen für Urenco-Anreicherungsanlage Almelo…," PA AA, B 72 (ZA)/123660/491.23/SB3 (July 7, 1978), 4.

This newfound disagreement over IAEA cascade access proved to be an intractable obstacle during Almelo FA negotiations. In October 1978, a meeting in the UK between IAEA and Troika officials reportedly "nearly collapsed" over the cascade access issue.[62] A U.S. cable reports that the IAEA's facility officer for Almelo "[could not] imagine an adequate safeguard [sic.] approach at Almelo, even granted extensive manpower and money resources, which does not allow access within the cascade area walls."[63] At this meeting, Troika representatives argued that classification policies, which had been discussed with the United States in the early 1970s (presumably the revised 1973 centrifuge classification guide), precluded inspector access to cascade areas.[64]

This was not the first time that the Troika's ties to U.S. security classification rules[65] had been used to argue against cascade hall access during the Almelo FA negotiations, although there appears to have been some confusion among stakeholders as to whether classification was a legitimate obstacle to cascade access at this point. From U.S. diplomatic correspondence, the FRG apparently brought up quadripartite classification policy as problematic for cascade access during the July 1978 Almelo meeting, prompting the IAEA to ask the United States for clarification about a potential conflict in this regard.[66] During a subsequent quadripartite meeting with Urenco personnel, however, the Urenco representatives stated that classification policy was not the

[62] U.S. Embassy Vienna to Department of State, Vienna 9627, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (October 24, 1978), 1.
[63] Ibid., 2.
[64] Ibid., 1.
[65] As discussed in the previous chapter, since 1973, U.S. and Tripartite security classification guides for centrifuge technology had been separate, although all parties had agreed to continue consulting with each other for consistency over centrifuge classification issues.
[66] U.S. Embassy Vienna, Vienna 6337, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (July 13, 1978), 4.

limiting factor on access, and that sensitive information, which motivated the non-access approach, extended beyond just classified information (presumably to commercially sensitive data).[67] This statement conflicted directly with the classification argument that was brought up in the October 1978 Almelo FA meeting. To complicate things further, the United States and the Troika were also currently engaged in discussion at the time to liberalize some aspects of centrifuge technology security classification. The United States was interested in releasing more information on its own centrifuge technology, now that it had chosen to commercialize the technology itself, and needed to convince potential customers of its technical merits, as the Troika had done earlier in the decade.[68] In particular, the United States was interested in declassifying the "approximate" length of centrifuges, the "approximate" total number of centrifuges in a plant, "some details" of piping arrangements, and "some details" on the distribution of electrical power within cascades.[69] The United States consulted the Troika on its plans in late 1978 and early 1979.[70] Although the U.S. Department of Energy (USDOE), which succeeded the USAEC and the U.S. Energy Research and Development Administration in managing U.S. gas centrifuge R&D, would continue to oppose inspector cascade access through the early 1980s, on nonproliferation grounds,[71] this initiative towards more liberal U.S. classification practices diminished the consideration of security classification in evaluating implications of inspector access, in U.S. policymaking circles.

[67] U.S. Embassy The Hague, The Hague 4204, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (July 29, 1978).
[68] James P. Van Der Rhoer to Dr. Gruber, Letter, PA AA, B 72 (ZA)/123660/491.23/SB5 (May 9, 1978).
[69] W.E. Fitzsimmons to A.J. van Galen Last, "Classification of Enrichment Technology – Discussions with the United States," PA AA, B 72 (ZA)/123660/491.23/SB1 (October 25, 1978).
[70] Auswärtiges Amt, "GUZ-Joint Committee 20.11.1978 in Den Haag," PA AA, B 72 (ZA)/123660/491.23/SB1 (November 23, 1978).
[71] Private communication with U.S. centrifuge safeguards expert (June 20, 2017).

As Almelo FA negotiations stalled through late 1978 and early 1979, political pressure for an agreement ramped up. In advance of the February 1979 IAEA BoG meeting, the Soviet Union made demarches in Bonn, Brussels, Rome, Washington, and London to press for the completion of Subsidiary Arrangements for facilities in Euratom States, which were now near two years overdue from the original deadline.[72,73] Previously, the BoG had granted extensions for this work, but on this occasion, the Soviet Union threatened to block attempts to push the deadline any further, citing a lack of political will from European countries.[74]

Renewed political pressure, along with the deadlock over the Almelo FA, motivated the IAEA to convene another Advisory Group meeting on enrichment safeguards, proposed for the week of June 11-15, 1979.[75] On this occasion, the United States proposed to convene an IAEA Consultants' Meeting in advance of the more formal Advisory Group meeting, noting how "complex" GCEP safeguards issues had become.[76] The IAEA assented to this request,[77] and a Consultants' Meeting was held at the IAEA in April 1979, with participants attending from the FRG, France, Japan, the Netherlands, the UK, the USA, and the IAEA.

[72] Article 40 of the IAEA-Euratom Safeguards Agreement obliges the IAEA, Euratom, and the relevant States to "make every effort" to conclude Subsidiary Arrangements within 90 days after entry into force of the Agreement, which occurred in May 1977.
[73] U.S. Embassy Vienna, Vienna 922, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (January 30, 1979).
[74] Ibid.
[75] U.S. Embassy Vienna, Vienna 852, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (January 29, 1979).
[76] U.S. Department of State, State 40080, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (February 16, 1979).
[77] U.S. Embassy Vienna, Vienna 2638, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (March 19, 1979).

The April 1979 Consultants' Meeting revealed the full extent of the policy divergence that had developed between GCEP safeguards stakeholders over the past two years. A U.S. summary of the meeting states that participants could only agree that "major questions remain concerning goals and objectives of IAEA safeguards at enrichment plants," that the Advisory Group planned for June 1979 should be postponed, and that IAEA knowledge of enrichment safeguards was "insufficient."[78] The United States attempted to bridge gaps between the Troika and IAEA position by drafting a position paper that made no judgments on access, but acknowledged that special MBAs may need to be established, due to the sensitivity of enrichment technology, and also cited the need for the IAEA to verify the absence of HEU production at facilities designed for LEU.[79] This initiative was not successful. Although the Dutch delegation generally voiced support for the U.S. position, supporting the consideration of facility misuse scenarios in safeguards, British and West German representatives were highly critical, not only of the safeguards measures that had recently come under consideration, but also of the very objectives that INFCIRC/153 safeguards sought to achieve. FRG delegates stated, as a "general point of principle" that the IAEA had no authority to look for undeclared material under INFCIRC/153-type safeguards,[80] yielding the logic that cascade access, motivated by the need to verify the absence of clandestine flows, was extraneous to the IAEA's mandate. Consideration of undeclared material in GCEP misuse scenarios in the 1977 Tokyo Advisory Group Paper, according to the FRG, set a dubious precedent.[81] UK representatives voiced concerns that if the IAEA were to search for "clandestine inputs" at enrichment facilities, then the IAEA would also have to do the same at all other nuclear

[78] U.S. Embassy Vienna, Vienna 3946, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (April 23, 1979), 1–2.
[79] Ibid., 2–3.
[80] Ibid., 5.
[81] Ibid., 5.

facilities. The cascade access debate, by this point, had essentially spawned a dispute among States over the general applicability of INFCIRC/153 safeguards to undeclared nuclear material. Frustrated by the events that had transpired over the past two years, UK representatives complained to the United States that "common perception of ground rules has been lost."[82]

Deadlock Sets In, 1979

The IAEA held two additional Consultants' Meetings in 1979 (one in lieu of the planned June 1979 Advisory Group Meeting), in hope of moving stakeholders closer to agreement. These efforts were made in vain. During this period, tensions developed between the United States and the Troika, which pressured the USA to reveal its own preferences regarding cascade access at its own planned enrichment facility, in Portsmouth, Ohio, thus bringing U.S. policy closer to the fray that had broken out between the Troika and the IAEA. By November 1979, after the final IAEA Consultants' Meeting, prospects for timely negotiation of an Almelo FA looked dismal.

Soon after the April 1979 Consultants' Meeting, the Troika requested that the IAEA postpone further meetings concerning safeguards measures for Almelo, possibly indefinitely.[83] While the IAEA continued pressing for access to verify misuse, the Troika and Euratom prepared a position paper stating, "Euratom and Agency are concerned only with the safeguarding of declared materials as declared to them through the normal reporting procedures and as received and verified on site by safeguards inspectors."[84] The IAEA was deeply opposed to suspending talks. If this were

[82] Ibid., 4.
[83] U.S. Embassy Vienna, Vienna 4350, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (May 3, 1979), 1.
[84] Ibid., 2–3.

to happen, the IAEA would have to apply ad-hoc safeguards procedures at Almelo on a limited basis (without cascade access), which would become a de facto precedent for safeguards at the plant. Furthermore, even though these ad-hoc measures would likely be insufficient for detecting misuse, IAEA staff worried that this deficiency would not be reported to Member States, for fear of damaging the IAEA's image.[85]

At this stage, the Troika also began to draw the United States into the Almelo FA debate. One reason cited for suspending negotiations was that the United States had not yet voiced a clear position on inspector access at its own GCEP, to be built in Portsmouth, OH.[86] In early April 1979, in response to questions from several States on whether the Portsmouth GCEP would be offered for safeguards under the U.S. VOA (and thus not subject to the national security exclusion), the United States began informing foreign officials, in confidence, that the facility would be added to the VOA list.[87] During a U.S. Senate hearing on the U.S. VOA in June 1979, however, the USDOE announced that the Portsmouth GCEP[88] was not included in the provisional list of eligible facilities, and that it would be only listed "prior to its operation provided safeguards are being applied by the IAEA at comparable facilities in non-nuclear-weapon states."[89] This position placed reciprocal pressure on the Troika to reach agreement over safeguards at Almelo.

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[85] Ibid., 2. Incentives still exist today for the IAEA to underreport safeguards challenges that it encounters, particularly in its annual Safeguards Implementation Report. See Trevor Findlay, *Proliferation Alert! The IAEA and Non-Compliance Reporting*, Belfer Center for Science and International Affairs (Harvard University, October 2015).

[86] U.S. Embassy Vienna, Vienna 4350, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (May 3, 1979), 1.

[87] U.S. Department of State, State 82206, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (April 3, 1979).

[88] The existing gaseous diffusion plant at Portsmouth was also not offered for safeguards.

[89] U.S. Senate, "IAEA safeguards agreement: Hearing before the Committee on Foreign Relations, United States Senate, 96th Congress, 1st session, on Ex. B, 95-2, Agreement with the International Atomic Energy Agency for the application of safeguards in the United States," (Washington: U.S. Government Printing Office, June 22, 1979), 6.

At the Consultants' Meeting in June 1979, which replaced the planned Advisory Group Meeting, the United States announced that it had started studying the safeguards implications of different inspector access levels,[90] perhaps to assure the Troika that it was working in good faith to adopt a policy on the issue. The meeting itself, however, was unproductive. Although the Netherlands appears to have been relatively silent, the FRG and UK once again argued against consideration of undeclared feed under INFCIRC/153, while all the IAEA's position papers cited undeclared feed as a relevant issue.[91] Although the IAEA nominally recognized the right of States to request Special MBAs at the meeting, it was clear to the U.S. delegation that the IAEA, in practice, did not intend to honor such requests.[92] At the end of the meeting, the UK, with the support of the FRG (to the dismay of the increasingly impatient Dutch Government), suggested delaying the Advisory Group Meeting, now scheduled for November 1979, even further, and replacing it with yet another Consultants' Meeting. While no decision was taken on the matter at the current meeting, the IAEA subsequently implemented the British suggestion, once again postponing the formal GCEP safeguards meeting.

During the deadlocked Consultants' Meetings of 1979, the UK and FRG adopted the same policy line regarding undeclared feed and cascade access. This behavior would contrast with the two countries' lines during the future HSP, during which the FRG held a much firmer position than the UK on these issues. Why did the UK take such a strong position initially, especially when the UK government had decided that limited cascade access, at least by Euratom inspectors, was

[90] U.S. Embassy Vienna, Vienna 6189, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (June 18, 1979), 4.
[91] Ibid., 2.
[92] Ibid., 3.

acceptable?[93] The UK may have sought to appease the FRG by initially taking a harder line, to keep the FRG committed to the Treaty of Almelo. The FRG had grown frustrated with tripartite enrichment cooperation over delays in expanding capacity at the Almelo site, which motivated construction of a Urenco enrichment facility on West German soil at Gronau, under FRG threats of withdrawal from the Treaty of Almelo. By tacking with the FRG early on, the UK demonstrated willingness to address the interests of its dissatisfied partner. Another key factor was that *limited* cascade access, at the time, was not on the table. The two models being discussed featured either no access to cascade halls, or unlimited access to cascade halls, as implemented by Euratom at Almelo (short of tearing centrifuge casings open). Since the only legal limitation on Euratom access rights is the necessity of access itself, the UK was compelled to argue forcefully that safeguards objectives justifying cascade access were irrelevant. In a private discussion with U.S. delegates at the June 1979 meeting, the UK articulated this logic.[94] During the HSP, by contrast, more attention was given to different degrees of inspector access within sensitive areas, allowing the UK to take a more moderate line.

Initial mentions of limited inspector access cropped up in late 1979, in the context of the U.S. study on access approaches at the Portsmouth GCEP. In response to an inquiry by Wolf Schmidt-Küster, of the FRG Ministry of Research and Technology (BMFT), as to the American position on access, the U.S. reported that it was considering "specified limited access" as a concept under which cascade access would be explicitly tied to a specific purpose, and under which "the frequency, permitted activities and measures, and destinations within the cascade hall would be subject to

[93] The UK's decision to negotiate limited cascade access with Euratom is detailed in Chapter 4.
[94] U.S. Embassy Vienna, Vienna 6189, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (June 18, 1979), 4.

carefully drawn conditions designed to avoid compromise of sensitive technology while achieving the desired goal."[95] Nevertheless, at this time, the United States demurred from committing to any particular approach, noting that it was still evaluating tradeoffs between safeguards effectiveness, risk of technology compromise, costs to the IAEA, and costs to the host country.[96] The U.S. government also argued that quadripartite security classification regulations were not "sufficiently precise" to make concrete conclusions about the nature of classified information that would be revealed via cascade access.[97] In sum, however, the United States had not yet fully studied the implications of different access regimes, and was not ready to commit to a particular access model or approach.

Amid these conditions, the final Consultants' Meeting, held in November 1979, failed to make any headway. Now that GCEP safeguards implementation in the United States, per U.S. policy, had been connected directly to GCEP safeguards in NPT NNWS, the Troika sought U.S. leadership on the access question. In advance of the meeting, UK officials stated that no progress would be possible on GCEP safeguards until the United States had made its mind up about access,[98] an observation which turned out to be prescient.

[95] U.S. Department of State, State 275372, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (October 22, 1979), 2–3.
[96] Ibid., 2.
[97] Ibid., 3.
[98] U.S. Embassy Vienna, Vienna 11542, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (October 24, 1979).

A New Multilateral Approach

By November 1979, GCEP safeguards development was far from achieving its desired result. Eight years had passed since multilateral discussions on GCEP safeguards began, and the Almelo FA was nearly three years overdue. Major political issues, notwithstanding the scope of INFCIRC/153 safeguards itself, lay in dispute, and consensus on the key matter of cascade access actually disintegrated over this time period. Continuing to hold IAEA Consultants' Meetings would be of little help, considering that the last three, dominated by political posturing at the expense of technical discourse, had failed to produce meaningful progress. Technical work on GCEP safeguards in the late 1970s, save for U.S. domestic efforts, was sparse. While the United States had devoted a $1.5 million annual program budget to developing safeguards tools for Portsmouth, the Troika States were hardly conducting any GCEP safeguards technical R&D, besides a Dutch program on intrusion detection and flow continuity verification for non-access areas.[99] Although interim ad-hoc IAEA inspections at Almelo, undertaken jointly with Euratom, would commence in early 1980, first focusing on UF_6 cylinder storage areas,[100] the frame of reference for negotiating a coherent, long-term safeguards approach had all but vanished. Something had to change.

In spring 1980, the U.S. Department of State began laying the foundations for what would become the HSP, observing that to this point, there existed "no sound basis for deciding on a detailed long-

[99] P.T. Good, "Minutes of a Meeting to Discuss Co-ordination of Research and Development on Safeguards for Gas Centrifuge Enrichment Plants," PA AA, B 72 (ZA)/129441 (June 13, 1980), 2–3.
[100] I.T. Manley to L.G. Wansink, "Enrichment Plant Safeguards," PA AA, B 72 (ZA)/129441 (January 7, 1980); S.F. Collins to H.W. Schleicher, "IAEA/Euratom Inspections at Almelo," PA AA, B 72 (ZA)/129441 (May 30, 1980).

term safeguards approach for Almelo."[101] The United States envisioned a "multilateral development and demonstration effort on enrichment plant safeguards instrumentation, equipment, and procedures in order to provide the basis for such a decision," expecting that agreement could be reached within one year.[102] At first, the United States invited each of the Troika governments to join this initiative, as well as Japan, whose pilot GCEP was also now operational and without a facility attachment.[103]

In June 1980, a U.S-Troika meeting took place to discuss details of the proposed technical cooperation. As the UK held chairmanship of the JC in 1980, the meeting took place at the UK Department of Energy (UKDOE), in London, with Fred Brown, a UKDOE official, chairing the talks. Despite reluctance from the Netherlands, which feared this work would become yet another "paper exercise"[104] (in the words of Fred Brown), the Troika took up the U.S. offer. At this meeting, the United States and the Troika established the framework for what became the HSP. Brown would chair the coordinating group for its entire duration. While multilateral R&D efforts would be coordinated by the new organization, participants would still finance and carry out their work independently.[105,106] The objective of this program, also agreed at the meeting, reflected U.S. intentions for a purely technical effort:

[101] U.S. Department of State, State 74297 (March 20, 1980), 1, U.S. Department of State FOIA Reading Room, Case Number M-2007-03097.
[102] Ibid., 1–2.
[103] Ibid., 3.
[104] F. Brown to P.J. Kelly, "The Joint Committee (JC) and the Hexapartite Safeguards Project," TNA FCO 96/1465/83, (October 30, 1981), 3.
[105] U.S. Department of State, State 144539 (June 2, 1980), U.S. Department of State FOIA Reading Room, Case Number M-2007-03097.
[106] P.T. Good, "Minutes of a Meeting to Discuss Co-ordination of Research and Development on Safeguards for Gas Centrifuge Enrichment Plants," PA AA, B 72 (ZA)/129441 (June 13, 1980), 4.

> "The objective of the programme (the co-ordinating group) would be to facilitate the application of international safeguards at uranium enrichment plants of the gas centrifuge type through the exchange of relevant information, the co-ordination of individual R and D efforts and technical consideration of various safeguards approaches."[107]

The Troika also consented to Japan joining the effort, along with the IAEA and Euratom. The United States also proposed that Australia, which was considering building a centrifuge enrichment plant, be invited to the group, although the FRG voiced concerns about Australia's inclusion, deferring a decision on an invitation.[108] A first full meeting for the new organization was scheduled for November 1980. Although only four parties had agreed to participate at this point, the Hexapartite Safeguards Project was born.

Reflections

The HSP sprung from an urgent need to resolve the very difficult situation that had arisen at the end of the 1970s. Could the disarray that that necessitated the HSP, however, been avoided? The breakdown in understanding between the IAEA and technology holders over use of non-access areas was a major factor in the deadlock in the Almelo FA negotiations. This was exacerbated by the fact that technology holders perceived that the IAEA was trying to reverse a previously agreed precedent that had been in place since 1972. The IAEA had essentially no say in implementing the original non-access 'working hypothesis.' At that time, the IAEA was not technically equipped to evaluate GCEP safeguards approaches, and had no access to facility design information, leaving it up to Member States to advise the IAEA what to do. Upon receiving technical details for Almelo

[107] Ibid.
[108] Ibid.

in 1978, and with greater technical background on GCEP technology,[109] the IAEA's assessment of access needs turned out to be different to the original understanding that had been agreed with the technology holders. Had the IAEA been equipped with the requisite technical knowledge from the start of multilateral GCEP safeguards talks, perhaps the IAEA would have spoken out against non-access to cascade areas. While this position would still have aggravated both the United States and Troika in the early 1970s, at least the IAEA would not have had to face undoing a precedent to which its Member States believed it had committed.

By the end of the 1970s, however, difficult political conditions regarding GCEP misuse were unavoidable. Disagreements between the United States and Troika, and the Troika and Euratom, over GCEP misuse verification (and INFCIRC/153 interpretation, in the former case) had already established GCEP safeguards as a political issue over the preceding decade. The FRG and Japan were highly sensitive to safeguards measures that sought to detect misuse involving undeclared material. IAEA safeguards implementation in the FRG and Japan, as NPT NNWSs with highly developed civil nuclear programs, had greater implications within the two countries than in almost all other NNWS. Tremendous diplomatic effort had been expended by the United States to push for FRG ratification of the NPT (via the conclusion of the IAEA-Euratom agreement), as well as Japanese ratification (which was predicated on the provisions of the IAEA-Euratom agreement).[110] After ratifying the NPT and submitting to NPT safeguards, the FRG and Japan were highly allergic to insinuations that they, as NNWS parties to the NPT that voluntarily submitted to comprehensive

[109] The IAEA began hiring inspectors with backgrounds in gas centrifuge enrichment in the mid-1970s. See U.S. Mission to the IAEA, IAEA Vienna 3247, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (April 22, 1975).
[110] Ryukichi Imai, "The NPT and Nonproliferation in East Asia: Views toward the 1990s," in *Beyond 1995: The Future of the NPT Regime*, ed. Joseph F. Pilat and Robert E. Pendley (New York: Plenum Press, 1990), 112.

IAEA safeguards, might possess undeclared material. Thus, the use of cascade access—particularly for verifying the absence of undeclared feed—would have still been the 'third rail' that it became in the late 1970s, and substantial effort would still have been required to resolve the issue.

Disputes over security and economic consequences of cascade access, in addition, would have been inevitable. As is evident in this chapter, while this issue was often quoted to support arguments for non-access, technology holders had not reached consensus on what information would be vulnerable, vis-à-vis different access regimes, along with the implications of revealing this information. The A.Q. Khan affair,[111] first publicized by the German media in March 1979,[112] although seemingly unmentioned in GCEP safeguards meetings that year, made stakeholders intensely aware of potential ramifications of leaks of centrifuge design information. The HSP provided the necessary venue for GCEP safeguards stakeholders to address security questions.

In sum, although some key aspects of disagreement in the 1970s could have been avoided, political discord over cascade access and the safeguards relevance of undeclared material and undeclared activities, which the HSP would ultimately have to address, persisted as difficult issues. As will be discussed in the next chapter, these political clashes, in combination with deteriorating relations within the Troika, would undermine the intended technical nature of the HSP, resulting in the

[111] A.Q. Khan, a Pakistani national, was employed by a subcontractor to UCN (the Dutch stakeholder in Urenco) in the early- to mid-1970s. Centrifuge design information, obtained illegally by Khan in the Netherlands, was used to develop Pakistan's own uranium enrichment program. See Adrian Levy and Catherine Scott-Clark, *Deception: Pakistan, the United States, and the Secret Trade in Nuclear Weapons* (New York: Walker & Company, 2007).
[112] Ibid., 57.

largely politically determined paradigm for misuse verification that still exists in GCEP safeguards today.

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Chapter 6 – The Hexapartite Safeguards Project

This chapter draws part of its content (primarily the portion that describes Troika coordination difficulties in 1981) from M.E. Walker, "The Hexapartite Safeguards Project Or: How I Learned to Stop Worrying and Love Multinational Enrichment," Proceedings of the 58th Annual Meeting of the Institute of Nuclear Materials Management (Indian Wells, CA, 2017).

At the outset of the 1980s, GCEP safeguards stakeholders needed to embark on a new approach for developing a GCEP safeguards approach. Altogether, six IAEA panels—a Technical Working Group in 1972, an Advisory Group in 1977 and four Consultants' Meetings (one in 1974, and three in 1979)—as well as the U.S.-Troika perimeter safeguards technical cooperation project, approximately two years of IAEA-Euratom-Troika Facility Attachment (FA) negotiations for Almelo and countless informal meetings over the past eight years had all failed to address how to verify the absence of GCEP misuse. Over the course of the 1970s, progress towards agreement went in the negative direction, in some respects. Common understanding of what would become the pivotal issue—cascade hall access for IAEA inspectors—eroded among the technology holders and inspectorates. The March 1980 U.S. proposal to establish a dedicated, time-limited effort to discuss GCEP safeguards approaches on a technical basis, replacing the open-ended series of intermittent series of meetings that had preceded it, offered an opportunity for a fresh start.

The Hexapartite Safeguards Project (HSP), the program spawned by the U.S. initiative, faced a tough path ahead. The question of cascade access, in recent years, had become inexorably intertwined with West German and Japanese opposition to IAEA authority for verifying the

absence of undeclared material and activities. Political concerns on the equity of safeguards application in nuclear weapon states (NWS) and non-nuclear weapon states (NNWS), both of which participated in the HSP, loomed large. Questions about the commercial and non-proliferation ramifications of inspector cascade access were unresolved. Hardly any meaningful safeguards equipment testing had taken place at GCEPs. Meanwhile, as divisions on safeguards philosophy grew within the Troika, the HSP served as a catalyst for sometimes-bitter disputes between the three partners.

Until now, very little has been written in the public domain on the HSP, as most of its associated activities, both political and technical, took place behind closed doors. This chapter, as do the three that precede it, makes use of documents obtained at multiple government archives that shed new light on policies adopted by HSP participants, as well as dynamics among them. These newly obtained records show that HSP deliberations on addressing misuse verification and the cascade access question, despite intentions for the HSP to handle GCEP safeguards issues on a technical basis, were subject to considerable political forces. The HSP's first year was almost entirely consumed with establishing a framework for evaluating different degrees of inspector access. While State participants carried out some technical work to support these discussions, momentum towards limited cascade access for verifying the absence of misuse (which would later become Limited Frequency Unannounced Access, or LFUA) only developed when the U.S. took the step to offer limited access at its own planned GCEP in Portsmouth, Ohio. Agreement was reached to pursue limited cascade access as the preferred option only after negotiation of the 'Sydney Compromise,' under which all parties agreed to equal application of the to-be-negotiated HSP safeguards approach in all HSP States, clear definition of inspection activities, and to address

security issues posed by inspector access to cascade halls. Much of the HSP's work during the second year addressed how the terms of the Sydney Compromise could be fulfilled in a manner satisfactory to all participants. Negotiation of LFUA inspection frequency, allowable verification equipment and measurements, and escort policies did not take place until the final few months of the HSP. In conclusion, the HSP was able to resolve the cascade access issue and produced a workable system for verifying the absence of GCEP misuse, including HEU production, which had eluded stakeholders for over a decade. However, key verification provisions for verifying the absence of misuse via cascade access were decided politically. Although the HSP was conceived as a technical forum, it addressed GCEP misuse verification primarily through political bargaining, and less through regimented, technically based verification measures that had characterized international safeguards prior to the HSP's end.

Getting the HSP Started

Following the June 1980 quadripartite meeting discussed at the end of the previous chapter, further arrangements needed to be made to convene the full membership of the HSP. Formal talks with Japan took place in August 1980, with the United States engaging on a bilateral basis in Tokyo for the first two days. During this time, A U.S.-Japan 'non-paper' was drafted, formalizing Japan's intent to participate in the collaborative development effort.[1] This paper, taking note of Australia's centrifuge enrichment development work, stated that Australia would be "directly affected"[2] by

[1] "Japan-U.S. Non-Paper on Enrichment Plant Safeguards" (August 14, 1980), attachment to "Report of Meeting US/Japan/Troika to Consider Establishing a Multi-national Co-ordinating Group on the Development of Safeguards at Gas Centrifuge Enrichment Plants," BArch, B 196/110542 (August 15, 1980).
[2] Ibid.

the activities of the group, even though Australia had not yet been approached formally. Now with six technology holders as proposed participants, the safeguards project was dubbed the "Hexapartite Project."[3] Formal guidelines for the Hexapartite Project were drafted as an Annex to the U.S.-Japan non-paper. The goal of the project was set to "develop, within 2 years, a common technical basis which can be used by the State involved and the IAEA for the implementation of safeguards approaches which are expected to be effective and efficient for specific facilities,"[4] by means of "the exchange of relevant information, the coordination of individual R and D efforts, and the technical consideration of various safeguards approaches."[5] In order to keep with the de facto precedent that had been maintained up to this point, and likely to assuage the FRG, Japan, and the UK's concerns, cascade hall non-access was to be used as a "reference case" for safeguards activities, with inspection approaches featuring cascade access approaches studied in parallel.[6] Finally, a bespoke system was set up for the exchange of information, some of which would be sensitive. Exchanging classified information among the six countries would cause legal difficulties. While the United States and Troika had long-standing (and generally compatible) classification regulations for centrifuge enrichment technology in place, Japanese legislation at the time prohibited the security classification of atomic energy information altogether.[7] Thus, an informal two-level 'classification' system was set up, wherein "Level 1" documents would be considered "unclassified" but for restricted distribution, and "Level 2" documents would be

[3] Ibid.
[4] Ibid., Annex.
[5] Ibid., Annex.
[6] Ibid., Annex.
[7] U.S. Embassy Tokyo, Tokyo 10345, RG 59 (AAD), *Central Foreign Policy Files 1973-1979* (June 12, 1979).

"classified" and handled by each party "pursuant to its regulations and procedures,"[8] but without elaboration regarding any specific handling practices.

On August 15, 1980, the U.S. and Japanese delegates met with Troika representatives in Tokyo to discuss further steps. On this occasion, the parties agreed that the United States would formally invite the IAEA to participate, and that the Troika would contact Australia. Furthermore, it was agreed that the IAEA and Euratom would only participate to the extent necessary to produce the requisite facility attachments[9]—the HSP was primarily to be a forum for the technology holders to exchange information and work out their differences among themselves.

No decision was taken, however, to issue a formal invitation to Euratom to take part in the HSP at the August 1980 Japan meeting. This would not take place until November 1980,[10] following the first HSP plenary meeting in Marlow, UK, and Euratom would not accept this invitation until mid-February 1981. Euratom was conspicuously reluctant to take part in the HSP, as the exercise offered an opportunity to erode Euratom's heretofore unrestricted access rights that it had exercised at Almelo for the last seven years. If the HSP were to conclude that unlimited cascade access was unnecessary, then the legal justification for Euratom's safeguards activities would disappear. Over the past year, the Troika, under UK JC chairmanship in 1980, had attempted to beat back cascade hall access rights for Euratom, to the inspectorate's frustration. Ad-hoc inspections at Almelo, which had taken place since early 1980, gave the Troika new ammunition

[8] "Japan-U.S. Non-Paper on Enrichment Plant Safeguards" (August 14, 1980), Annex.
[9] Original German: "IAEA-und Euratom-Beteiligung soll nur auf Ebene der Kontrollbehoerden, die fuer "Lizenzierung" (Facility Attachment) der Anreicherungsanlagen zustaendig sind, erfolgen." FRG Embassy Tokyo to Bonn AA, "Safeguard-System fuer den Betrieb von GUZ-Anreicherungsanlagen," PA AA, B 72 (ZA)/129441 (August 15, 1980), 2.
[10] P.J. Graham to E. Noel, "Hexapartite Safeguards Project," TNA FCO 96/1464/2 (January 5, 1981).

against Euratom. As the IAEA reportedly considered these activities to support Article 90 statements,[11,12] the Troika could then argue that while the IAEA's ad-hoc inspections were being implemented, cascade access would not need to be granted, as safeguards conclusions (at least for its purposes) could be drawn adequately under the status quo. The UK Government, acting on behalf of the Troika as JC chair, made this argument to Euratom in May 1980, requesting an exchange of letters between the IAEA and Euratom, with Troika approval, formally committing both inspectorates to non-access while ad-hoc inspections were underway.[13] Euratom's H.W. Schleicher aggressively fought back against the Troika request, arguing that States had no authority under the IAEA-Euratom safeguards agreement to approve nor disapprove of ad hoc inspection activities.[14] Furthermore, Schleicher noted that as Almelo was physically located in the Netherlands, the UK had no authority, in any case, to make requests concerning safeguards at Almelo. In Euratom's response, Schleicher wrote that he would not take any action on the letter until he received a "formal communication on the subject through the correct channels."[15]

In July 1980, as the Troika worked to resend its request through the Dutch Government, Euratom—perhaps to make a point—conducted an inspection at Almelo with cascade hall access.[16] Euratom

[11] Article 90 of the IAEA-Euratom Agreement (similarly to paragraph 90 of INFCIRC/153) charges the IAEA with reporting to Euratom the results of inspections, as well as conclusions drawn from verification activities. The implication in invoking the ad-hoc inspections as a basis for Article 90 statements is that the IAEA's verification activities at Almelo at the time were sufficient for drawing safeguards conclusions, and that no additional activities or access was required.
[12] S.F. Collins to H.W. Schleicher, "IAEA/Euratom Inspections at Almelo," PA AA, B 72 (ZA)/129441 (May 30, 1980), 1.
[13] Ibid., 2.
[14] H.W. Schleicher to S.F. Collins, "IAEA/Euratom inspections at Almelo: Your letter dated 30 May 1980," attachment to W. Bowers to Van Galen Last, "IAEA/Euratom Inspections at Almelo," PA AA, B 72 (ZA)/129441 (June 24, 1980), 1.
[15] Ibid., 2.
[16] W.F.S. Rickett to Fullerton and Manley, "Troika Safeguards Problems," TNA FCO 96/1464/3 (January 28, 1981).

inspectors, of course, had been afforded access by the Dutch Government for several years at this point, since November 1973. The stated position of the Netherlands since then had always been that Euratom inspectors had the right to access Almelo's cascade halls, under Article 81 of the Euratom Treaty.[17] Clearly, asking Euratom to cease inspections in cascade halls, which had previously been carried out pursuant its Article 81 authority, would contravene Dutch government policy. In the end, a different arrangement was made: the Dutch government and Euratom made a 'gentlemen's agreement' under which Euratom would not seek cascade access during the interim ad-hoc joint IAEA-Euratom inspections,[18] as the IAEA had already committed to not pursuing cascade access during these activities. Verification activities undertaken solely by Euratom would not be affected by the informal arrangement,[19] and the Dutch Government maintained that during the HSP, if Euratom inspectors were to request cascade access, the request would be approved.[20]

Prior to formally joining the HSP (and after being formally invited), Euratom attacked the UK government on the cascade access question at Capenhurst, likely as a tactical measure to build bargaining leverage going into the HSP. Unlike the Netherlands, the UK had never permitted cascade access for Euratom inspectors at Capenhurst. Nevertheless, the British government was content with cascade hall access on a restricted basis, under which disruption to plant operations and the transfer of sensitive information to inspectors would be minimized, and had already

[17] The first Euratom inspection at Almelo with cascade access is described in Chapter 4 of this dissertation. See also Ibid., 1; F. Brown to J.K.L. Thompson, "Euratom Safeguards – Inspector Access to the Cascade Areas of the Almelo Plants," TNA FV 70/17/2/6 (November 20, 1973), 2.
[18] Rickett to Fullerton and Manley, TNA FCO 96/1464/3 (January 28, 1981), 1.
[19] Cascade access by Euratom at Almelo seems to have been quite infrequent, however, seemingly for periodic design information reverification. As of July 1980, the last inspection with cascade access took place in January 1979. See Ibid., 1.
[20] L.G. Wansink, "At the next meeting of the joint committee…," PA AA, B 72 (ZA)/129441 (February 16, 1981).

advocated with Euratom for application of such an approach at Capenhurst in the mid-1970s.[21] The UK's initiative was rebuffed by Euratom, however, which insisted on completely unrestricted access rights for its inspectors at the time.[22] This deadlock resulted in maintenance of the status quo: no cascade access. In January 1981, however, Euratom inspectors began requesting visits to the cascade halls at Capenhurst, arguing that the Dutch government was allowing cascade access[23] (given that the gentlemen's agreement only applied to ad-hoc IAEA-Euratom joint inspections, this statement was not inaccurate). On 30 January 1981, Leonard Williams, a British national and Director-General for Energy (DG-ENER) at the Commission of the European Communities, telephoned Ivor Manley, Head of the Atomic Energy Division at the UK Department of Energy (UKDOE), to warn him that he was being pressured by Euratom[24] to formally request cascade hall access for its inspectors.[25] On 10 February 1981, Williams made this request to the UKDOE in writing, stating that Euratom inspectors would need to access cascades at Capenhurst "say once per year" to verify that cascade reconfiguration had not taken place—essentially performing Design Information Verification (DIV).[26] Furthermore, Williams argued that giving Euratom access would not necessarily create a precedent for IAEA access, since the legal frameworks for the two inspectorates differed.[27] The UK Government, however, viewed the situation differently. If the UK were to succumb to Euratom's—now formal—request, that act would constitute an admission that cascade access, on unrestricted terms, was required for effective GCEP

[21] Fred Brown to Peter Irwin, "Access to Centrifuge Enrichment Facilities," UK National Archives (TNA) FV 70/17/1 (March 15, 1976).
[22] Fred Brown to Peter Kelly, "The Hexapartite Safeguards Project (HSP): Tokyo Meetings 4-13 November 1981," TNA FCO 96/1465/91 (November 19, 1981).
[23] Rickett to Fullerton and Manley, TNA FCO 96/1464/3 (January 28, 1981), 1.
[24] The Director of Euratom Safeguards is subordinate to the Director-General for Energy.
[25] I.T. Manley, "Note for the Record: Euratom," TNA FCO 96/1464/5 (January 30, 1981).
[26] Leonard Williams to I.T. Manley, "Access of Euratom Inspectors to Capenhurst Centrifuge Enrichment Plants," TNA FCO 96/1464/10 (February 10, 1981).
[27] Ibid.

safeguards.[28] Thus, the UK denied Euratom's request, and Schleicher wrote to Capenhurst's management, stating that the UK's refusal constituted a violation of the Euratom Treaty, and that the matter would be raised formally with the UK Government.[29] Schleicher's move, in this case, appears to have only been a tactical move to pressure the UK and the other HSP States into doing meaningful work over its two-year period. Approximately four days after news of the Capenhurst Euratom safeguards 'violation' reached the UK Government, Euratom announced its formal participation in the HSP.[30] No archival evidence could be found indicating that Euratom pursued the issue any further at the time. It can be inferred that Euratom deliberately propagated the chain of events leading up to the Capenhurst safeguards breach so that it if the HSP were to end in failure or inconclusively, Euratom would immediately have a card to play against the UK, instigating legal arbitration over cascade access which the UK would likely lose.

Euratom's strategy in early 1981 is consistent with its comments (along with those of the IAEA) at the first HSP meeting in Marlow, held on November 5-7, 1980. Although some of the attendees—in particular, Euratom, as well as the IAEA—had not yet committed themselves to taking part in the HSP, all six technology holders and the two inspectorates were represented at the meeting, which was largely held to officially establish the institutional and logistical frameworks for the Project. Both Euratom and the IAEA made clear that their continued participation in the HSP would be conditional on the HSP demonstrating that was working in good

[28] F. Brown to I.T. Manley, "Access of Euratom Inspectors to Capenhurst Centrifuge Enrichment Plants," TNA FCO 96/1464/12 (February 13, 1981).
[29] Ibid.
[30] F. Brown to R. Smith, "Hexapartite Safeguards Project," TNA FCO 96/1464/13 (February 17, 1981).

faith to develop a GCEP safeguards approach, instead of being yet another delay tactic crafted by the technology holders.[31]

The Netherlands, unlike its Troika partners, also stressed the urgency of the HSP's goal, declaring its determination to conclude with the IAEA an FA for Almelo at the end of the HSP, at the very latest.[32] This talking point was supported by the United States and Australia.[33] Throughout the HSP, the Netherlands would continue to advocate for expediting the Project's timeline, particularly when other parties supported delaying its work. At this early stage, the Dutch government insisted, along with the inspectorates, on scheduling four HSP plenary meetings over the following twelve months, with the fourth meeting serving as a detailed review of the first year of work.[34] Parties agreed to hold a second meeting in March in the Netherlands, and the third meeting in the USA in June 1981.[35] According to Fred Brown, the HSP's Chairman, the agreed plan for the first year was to collect information on GCEP characteristics, safeguards technology and available safeguards measures, while the second year of the HSP would be devoted to defining and evaluating safeguards strategies based on this information.[36]

[31] FRG London Diplo to Bonn AA, "GUZ-Anreicherungsanlagen Heksapartite Safeguards Project: Delegationsbericht von der ersten Sitzung 5.-7. November in Marlow (Urenco)," Telegram No. 1772, PA AA, B 72 (ZA)/129441 (November 12, 1980), 1.
[32] Ibid.
[33] Ibid.
[34] F. Brown to P.J. Kelly, "The Joint Committee (JC) and the Hexapartite Safeguards Project," TNA FCO 96/1465/83 (October 30, 1981), 3.
[35] FRG London Diplo to Bonn AA, Telegram No. 1772 (November 12, 1980), 2.
[36] Fred Brown, "The Hexapartite Safeguards Project: A Review by the Chairman," IAEA-SM-260, in *Nuclear Safeguards Technology 1982: Proceedings of a Symposium* (Vienna: International Atomic Energy Agency, November 8-12, 1982), 493.

To divide up the information collection and analysis task, the HSP's work was organized into four teams, each led by one of the technology holders, as shown in Table 6-1. HSP teams would carry out their work and meet both in conjunction with plenary meetings, and separately as needed. It was intended that Team 1 would complete its work first, and then pass its findings to the three other teams, which would apply information on facility characteristics to their own work. Beyond organization of the four teams, the first HSP meeting also set up procedures for official communications, implemented the document "classification" system discussed in Tokyo, and set up procedures for covering costs incurred.[37] Perhaps most importantly, the HSP's mission was also officially agreed: the exchange of relevant information, the coordination of R&D programs, as well as the development of a safeguards concept that could serve as a basis for the negotiation of FAs for existing or planned enrichment plants between inspectorates and relevant countries.[38] In doing so, States would consider in parallel the implementation of safeguards approaches with and without cascade access.

Table 6-1: HSP Team Structure

Team Number	Leader	Area of Study
1	Japan	Evaluation of facility characteristics
2	UK	Containment and surveillance measures
3	Australia	Nuclear material accountancy
4	USA	Safeguards strategies (including cascade access strategies)

[37] Ibid.

[38] In German: "Die Rahmenvereinbarung sieht den Austausch relevanter Informationen, die Koordinierung der F'E Programme sowie die Entwicklung eines Safeguards-Konzeptes vor, das den Kontrollbehoerden und betroffenen Laendern als Basis fuer die Verhandlungen ueber Anlagenspezifische Anhaenge fuer eksistierende oder geplante Anreicherungsanlagen dienen kann." FRG London Diplo to Bonn AA, Telegram No. 1772 (November 12, 1980), 1.

Difficulties Coordinating the Troika Line

As the HSP got underway, the Troika worked to coordinate its involvement in the effort. Despite the three partners disagreeing on the HSP's central question, a common Troika position was desirable, both for legal and commercial reasons. First, the Treaty of Almelo obliged the JC to consider and make decisions on safeguards issues (to which the HSP was clearly applicable), as well as classification policy.[39] JC decisions were to be taken by a unanimous vote.[40] Thus, it behooved the Troika governments to coordinate their positions on GCEP safeguards issues for the HSP, because any safeguards measures or approaches agreed to by any of the three governments, including approval of any FAs based on an HSP safeguards approach, would require JC approval. Furthermore, an open display of disunity within the Troika would reflect poorly on its ability to manage the Urenco enterprise, deterring customers and potential technology licensees, such as Japan and Australia.[41] On this basis, the Troika tried at the start of the HSP to put forth a united front. In reality, however, tripartite coordination proved to be difficult, leading to several political disputes, particularly during the HSP's first year, when the question of access regimes was still open.

[39] "Agreement between the United Kingdom of Great Britain and Northern Ireland the Federal Republic of Germany and the Kingdom of the Netherlands on Collaboration in the Development and Exploitation of the Gas Centrifuge Process for producing Enriched Uranium, Almelo, 4 March 1970," Treaty Series No. 69 (London: HM Stationery Office, 1971).
[40] Ibid., art. II.2.
[41] At the time, for example, the Troika was hoping to construct a GCEP using its centrifuge technology, as well as technical cooperation with Japan. See "Report of the Expert Group on Collaboration with Australia," JC/80/8; "Possible Collaboration with Japan," JC/80/9, attachments to W.F.S. Rickett to A.J. Van Galen Last and W. Boucsein, "Papers for the Next Joint Committee Meeting: 9 December," CW/138/0148, PA AA, B 72 (ZA)/129438 (November 18, 1980).

In a JC meeting in December 1980, the Troika States agreed that no cascade access would be granted to "IAEA/Euratom inspectors"[42] during the duration of HSP, and that the three governments would coordinate their inputs to the HSP through the Troika Safeguards Working Group (TSWG),[43] whose membership consisted of the Urenco Board, as well as each national Urenco shareholder. Despite this agreement, however, Bob Wansink, who would go on to chair the JC in 1981 as the Chairman's seat rotated to the Netherlands, pointed out that it could be difficult to study cascade access approaches if inspectors were not allowed to go inside cascade halls,[44] heralding further Dutch dissent to come. Shortly after the JC meeting, the Urenco Board decided that a "one policy, one voice" line was to be maintained by the Troika at the HSP, and that the bloc should support a non-access approach.[45] This plan, however, quickly unraveled. While the UK and FRG governments thought the three partners had agreed for all technical contributions to be coordinated by the TSWG, the Dutch government perceived the situation differently.

On February 4, 1981, Wilfred Rooke, Urenco's Company Secretary, telephoned an official at the UKDOE. Rooke reported that he had heard that a staff member at UCN (the Dutch Urenco shareholder) was about to send a telex to the leader of HSP Team 4, whose task was to consider the access question. The message, to Rooke's knowledge, stated that UCN believed that "full access was necessary for the proper safeguarding of centrifuges."[46] Rooke reported, in addition,

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[42] In practice, "IAEA/Euratom inspectors" meant IAEA and Euratom inspectors conducting joint inspections, as in the Netherlands-Euratom-IAEA gentlemen's agreement discussed earlier in this chapter.
[43] "Minutes of the Meeting of the Joint Committee of the Tripartite Uranium Enrichment Collaboration Held in Capenhurst at 09.30 on Tuesday, 9th December 1980," PA AA, B 72 (ZA)/129440 (December 9, 1980), 3.
[44] Ibid.
[45] Wilfred Rooke to I.T. Manley (December 16, 1980), attachment to W.F.S. Rickett to I.T. Manley, "The Joint Committee," TNA FCO 96/1464/7 (January 16, 1981).
[46] P.G.P.D. Fullerton to I. Manley, "Hexapartite Study on Safeguards," TNA FCO 96/1464/8 (February 4, 1981).

that "the Germans… were 'totally concerned'" about UCN's message, and urged the UK government to intervene by contacting Bob Wansink, now Chairman of the JC.[47] In response, Ivor Manley, still Head of the Atomic Energy Division at the UKDOE, quickly telexed Wansink, urging him to prevent UCN from sending the message before the situation could be discussed in a meeting, and warning "if such a message were to be sent it would ruin any prospects for a common Troika position in the HST [sic.]"[48] At a meeting in The Hague later that week between Wansink, Rooke, UCN representatives, and Dutch government officials, it was clear that a deep misunderstanding had transpired at the December 1980 JC meeting. While Dutch Ministry of Foreign Affairs officials confirmed that they would "subscribe to the non-access model throughout the period of the study," the Dutch government had also understood that technical analyses submitted to the HSP would not need to undergo vetting.[49] Furthermore, the Dutch government had misunderstood the JC's decision to give coordination authority to the TSWG—instead, the Dutch understood that the JC's Subcommittee on Safeguards (SOS), which was defunct at the time, was to be reestablished and given power only to coordinate political positions for the Troika. To facilitate objective technical work, Dutch government officials proposed the system to which they had perceived that the JC had agreed: that the SOS be reconvened to coordinate political issues, while the TSWG would handle technical contributions, acting independently from the SOS.[50]

[47] It is unclear whether "the Germans" were associated with Uranit/Urenco or the FRG government. Ibid.
[48] Manley to Wansink, TNA FCO 96/1464/9 (February 5, 1981).
[49] Wilfred Rooke, Meeting Note (February 8, 1981), attachment to W. Rooke to W. Schmidt-Küster, PA AA, B 72 (ZA)/129441 (February 11, 1981).
[50] Ibid.

In addition to the threat of Dutch defection, the Troika also had to deal with toning down the FRG's controversial position on undeclared activities and feed. Throughout the HSP, the FRG would persistently block any discussion addressing undeclared feed and enrichment capacity, arguing that INFCIRC/153 did not address undeclared material and activities. At the beginning of the HSP, the FRG government (specifically, the Federal Ministry of Research and Technology, or BMFT) went even further, taking the position that GCEP misuse was implausible, and should not be considered in the design of a GCEP safeguards approach.[51] If facility misuse were deemed irrelevant to GCEP safeguards, then the only applicable safeguards objective would be verifying non-diversion of declared material, which would not necessitate cascade access, given the low inventory of material in cascades. Under this assumption, as well as security concerns and operational disruptions associated with cascade access, the FRG argued that the cascade access approach was neither necessary nor desirable.[52]

An SOS meeting was held on February 18, 1981 to discuss the Dutch restructuring proposal, as well as the Dutch paper that had prompted the recent confusion, and a recently-drafted German paper that argued in favor of excluding undeclared material from GCEP safeguards

[51] A German HSP position brief prepared in February 1981 states, "Wegen der technisch und organisatorischen Schwierigkeiten eine überwachte Anlage, die für eine Niedrig-Anreicherung ausgelegt ist, zu mißbrauchen, wird diese Abzweigungsstrategie als nicht plausibel angesehen und als Auslegungskriterium für eine Konzeptentwicklung ausgeschlossen." This translates to: "Because of technical and organizational difficulties in misusing a facility under safeguards that is configured for low enrichment, this diversion strategy should be deemed implausible and excluded as a design criterion for concept development." The underlying assumption behind the FRG position was that NPT Non-nuclear Weapon States, by virtue of them being NPT signatories, would not undertake undeclared activities. At the time, this rationale was not uncommon among States. See Rüdiger Gerstler, "Abstimmung der Randbedingungen für Konzeptentwicklungen und Vorschläge zur Vorgehensweise in den anstehenden internationalen Diskussionen bezüglich Kontrollmaßnahmen für GUZ-Anlagen," BArch, B 196/110542 (February 17, 1981).
[52] Ibid.

considerations.[53] Although the German paper was not discussed,[54] British and German officials put forth a scathing critique of the Dutch paper, arguing that its evaluation of C/S measures and subsequent conclusion had little technical support, and that its claim that the proliferation risk attributable to cascade access was only "slight" was unsubstantiated.[55] Regarding coordination by the SOS, the Troika agreed that HSP coordination should be carried out between governments (and not within the TSWG), for the sake of avoiding further surprises and embarrassment through contradictory positions. In line with the Dutch proposal, it was agreed that the JC SOS would be reconstituted to provide a venue for the Troika governments to coordinate political positions for the HSP. A dispute arose, however, over how technical-level contributions were to be coordinated. This issue was particularly pertinent, as HSP participants were expected to prepare papers outlining possible access strategies for Team 4 by summer 1981, for discussion at the third HSP plenary meeting. A Dutch representative suggested national representatives could speak in their personal capacities, but the FRG and UK disapproved of the idea, arguing that differences in the Troika position even on technical matters could be harmful.[56] The UK, however put forward a compromise: instead of individually sending in papers, the Troika could commission the TSWG to prepare a joint document for Team 4 objectively considering the pros and cons of different access and non-access approaches, thus covering all of the Troika positions without demonstrating any preference for any particular national perspective. The TSWG's work would then be jointly

[53] R. Gerstler and G. Stein, "The Assumption Underlying Possible Safeguards Strategies Including Access to the Cascade Area," Attachment to [Title Illegible], TNA FCO 96/1464/11 (February 18, 1981).
[54] It is possible that the German paper (which ran only two pages) was only drafted to demonstrate the possible embarrassment and confusion that could result from the Troika States sending in contradictory papers.
[55] J.W. Thorp, "Note of a Meeting of the Joint Committee's Sub-Group on Safeguards on Safeguarding of Enrichment Plants, The Hague, 18 February 1981," TNA FCO 96/1464/16 (February 20, 1981).
[56] Ibid., 2.

cleared by national governments through the SOS.[57] This process would be applied to all future Troika HSP technical contributions, meaning that these documents would be vetted and coordinated at the political level by national governments.

The SOS adopted the UK proposal, and directed the TSWG to prepare a technical paper on access approaches for Team 4. In doing so, the TSWG was also charged with considering both the diversion of declared material, and the possibility of undeclared material or equipment being used in misuse scenarios, for the sake of being able to engage with other HSP participants, which were bound to raise these issues.[58] Although this plan was approved by the SOS, the BMFT almost immediately began criticizing the TSWG's mandate for preparing the Team 4 paper. On February 23, 1981, Wilhelm Boucsein, of the BMFT, wrote to the Dutch Ministry of Foreign Affairs, complaining that the TSWG should not only evaluate access strategies, but also consider the probability of diversion and misuse scenarios that they address.[59] In addition, Boucsein wrote,

> "Prerequisite for the safeguard system ist [sic.] the knowledge of plausible misuse and diversion strategies. In the case of a GUC [gas ultracentrifuge] plant designed for low enrichment and so regarded under INFCIRC 153 plausible diversion scenarios are connected with the diversion of LEU, U_{not} [sic.] and U_{depl}. The misuse of a plant for undeclared high enrichment should be understood as a violation of declared design information. More theoretical misuse and diversion strategies are connected with the existence of undeclared feed material and equipment within the cascade area."[60]

By eliciting the FRG's assessment of diversion and misuse likelihoods, the Team 4 paper would then clearly be prejudicial to non-access approaches, as the diversion and misuse scenarios

[57] Ibid.
[58] Ibid.
[59] Boucsein to P. Verbeek, TNA FCO 96/1464/20 (February 23, 1981).
[60] Ibid.

addressed by cascade access would be portrayed as improbable or irrelevant. Such a formulation contravened the compromise proposed by the UK at the recent SOS meeting. For the time being, to satisfy the FRG, the Troika reached an informal understanding at the second HSP meeting in Boekelo, NL in mid-March 1981, to give "minimum recognition" to undeclared activities at GCEPs in HSP submissions without spelling out the FRG's rationale for why they should be disregarded,[61] effectively glossing over this source of disagreement within the Troika. Within the HSP as a whole, this concept was agreed and summarized in Boekelo as: "Safeguards will ensure that all nuclear material passes through strategic points and that the plant is operating as declared in the Design Information Data."[62] This construction, however, deliberately avoided explicit statements on the relevance of undeclared feed and equipment scenarios. As will become apparent later, however, this so-called 'Boekelo Understanding' would not prevent German criticisms on undeclared material from re-emerging.

A Second Attempt at U.S.-Troika Equipment Field Testing

With the onset of the HSP came a renewed interest from the United States in field testing equipment that to date had not been used in a commercial-scale GCEP. In the late 1970s, U.S. work accelerated on GCEP safeguards equipment, particularly non-destructive assay (NDA) instruments, as plans were put in place to construct the Portsmouth GCEP.[63] Neutron and gamma

[61] Brown to Kelly, TNA FCO 96/1465/83 (October 30, 1981).
[62] UKDOE Atomic Energy Safeguards Office, "The Joint Committee Meeting, The Hague, 14 May 1981; Agenda Item 5: Safeguards on Enrichment Installations" (May 11, 1981), attachment to F. Brown to I.T. Manley, "Meeting of the Joint Committee, 14 May 1981," TNA FCO 96/1464/25 (May 11, 1981).
[63] Nathan H. Hurt, "Enrichment Plant Management and Safeguards," GAT-NM-18, Proceedings of the 19th Annual Meeting of the Institute of Nuclear Materials Management, (Cincinnati, OH, 1978); Roddy B. Walton, *The Feasibility of Nondestructive Assay Measurements in Uranium Enrichment Plants*, LA-7212-MS, (Los Alamos Scientific Laboratory, April 1978).

detection equipment was applied for measuring deposits in cascade piping, and neutron area monitoring had been flagged as a potential technique for characterizing the operating status of a cascade at the Oak Ridge Gaseous Diffusion Plant, for example.[64] During the first year of the HSP, U.S. national laboratories, including Los Alamos Scientific Laboratory (as it was known at the time), Sandia National Laboratories, Brookhaven National Laboratory and Oak Ridge National Laboratory, worked on developing instruments for use in cascade hall inspections, with test cascades at Oak Ridge serving as a demonstration facility. Los Alamos was designing a neutron slab detector for measuring neutron fields inside cascade halls, as well as a 'dipstick' high purity germanium (HPGe) detector in collaboration with Oak Ridge that could be dropped between 4 centrifuges to calculate the enrichment of materials inside by measuring the ratios between gamma peaks associated with ^{235}U and ^{238}U. Sandia, meanwhile had developed the ROBIN system—an abbreviation for 'ROBot INspector,' which consisted of radiation detection, location, video, and data collection modules and could be operated by an inspector in both access and non-access areas. The ROBIN's radiation detection module used a high purity germanium detector to measure gamma emissions from ^{235}U and ^{238}U, for measuring the enrichment of material in cascade areas.[65] The auspices of the HSP offered a new opportunity for the United States to conduct field experiments with this equipment, perhaps with greater prospects for results this time around, now that the need to develop a GCEP safeguards approach was urgent—in contrast with initial U.S.-Troika GCEP safeguards development in the 1970s. These hopes, however, were quickly dampened.

[64] Walton, *The Feasibility of Nondestructive Assay Measurements in Uranium Enrichment Plants*, 43–44.
[65] Interview with U.S. safeguards expert (August 1, 2017); F.F. Dean, "ROBIN: a way to collect in-plant safeguards data with minimal inspector access," SAND-82-1588C (Sandia National Laboratories, 1982).

Although the Dutch government was highly receptive to a U.S. proposal at the Boekelo HSP meeting to carry out testing of American equipment at Almelo, the FRG and UK were skeptical of this approach. On April 6, 1981, Aldert Jan van Galen Last, of the Dutch Ministry of Foreign Affairs, informed the UKDOE and BMFT that the U.S. had voiced its interest in testing safeguards instrumentation at Almelo. While van Galen Last did not mention the type of equipment in the U.S. proposal, he did mention that the measurement devices could be used in the context of limited cascade access and that the Dutch government favored giving cascade access to U.S. personnel, "as far as necessary for the purposes of these tests… because the practical testing of equipment that might be used in the framework of a limited access strategy seems indispensable for the proper evaluation of that safeguards strategy."[66] Both the FRG and UK were staunchly opposed to the Dutch policy. Not only were they provided with no information on what devices were to be tested, there existed no precedent for foreign nationals being given access to cascade areas at Urenco facilities to carry out measurements. During the 1974–1975 testing campaign, operation of U.S. equipment was carried out by Dutch personnel. Furthermore, now that the United States was building its own GCEP, the FRG and UK were now sensitive to whether access to American GCEPs would be granted to Troika personnel on a reciprocal basis.[67] To this point, the United States had made no commitments in this regard. In response, the UK drafted a telegram declining consent for U.S. personnel to enter the Almelo cascade halls, although the message did indicate that the UK was content with U.S. access to non-sensitive areas of the plant,[68] unlike in the mid-1970s, when Americans were not given access to the plant at all. The FRG government voiced

[66] A.J. van Galen Last to Rickett and Boucsein, "Hexapartite Safeguards Project (HSP)" (April 6, 1981), attachment to W.F.S. Rickett to F. Brown, "Hexapartite Safeguards Project (HSP)," TNA FCO 96/1464/28 (April 10, 1981).
[67] Ibid., 1.
[68] UK FCO to Embassy The Hague, Telegram No. 62, TNA FCO 96/1464/30 (April 14, 1981).

similar concerns, and Urenco stated its opposition "to any access of U.S. personnel for any reason to Urenco's enrichment plants."[69] Outnumbered, the Dutch government deferred to its partners, although van Galen Last wrote (to the UKDOE and the BMFT) that "if [no U.S. access to cascades] would cause problems for the inplant testing of safeguards equipment we will raise this pint [sic.] again."[70] Although the Netherlands fell back in line with the Troika, as it had done the case of UCN's Team 4 contribution, this episode nevertheless illustrates the disparity on GCEP safeguards that had grown within the Troika.

Maintaining Troika Solidarity: Facility Tours and the Troika Team 4 Paper, Spring-Summer 1981

UK and the FRG also fought against access to Almelo being given to any HSP participants, when the question of Almelo tours arose in the run-up to the 2nd HSP Plenary. The Netherlands first raised the issue in the February 18 SOS meeting, and the UK[71] and the FRG[72] reacted negatively to the proposal, with the Germans arguing (using rather circular logic) that there would be no need for a visit to take place until after the HSP had determined whether access would be useful of not. Moreover, the Urenco Board expressed irritation that Boekelo had been chosen by the Netherlands as the location for an HSP meeting, since it was so physically close—12 miles, as the crow flies—

[69] W. Rooke to A.J. van Galen Last, TNA FCO 96/1464/32 (April 21, 1981).
[70] A.J. van Galen Last to Boucsein and Rickett, "Hexpartite [sic.] Safeguards Project," TNA FCO 96/1464/33 (April 24, 1981).
[71] FCO to The Hague, "Visit to the Urenco Enrichment Plant at Almelo During Meeting of the Hexapartite Safeguards Project (HSP)," TNA FCO 96/1464/14 (February 18, 1981).
[72] Boucsein to Verbeek, Fernschreiben Nr. 1018, attachment to F. Brown to I.T. Manley, "Meeting of the Joint Committee, 14 May 1981," TNA FCO 96/1464/25 (May 11, 1981).

to Almelo, implying that a tour might be offered in addition to the HSP meeting.[73] In response to this widespread criticism, the Dutch Government withdrew the request, and the Almelo tour was not offered to HSP attendees.[74]

The UK, in defending its opposition to the Almelo visit, argued that a tour should only be offered under a principle of reciprocity between technology holders—specifically, U.S. personnel could visit Almelo only when the United States showed willingness to do the same at the Portsmouth GCEP, once operational.[75] A tour of the Portsmouth GCEP construction site, in its current state, in the eyes of the UK, would be an insufficient bargaining chip to trade for an Almelo visit. Nevertheless, after the United States extended an invitation to HSP participants to tour the Portsmouth site prior to the 3rd HSP plenary meeting in Washington DC,[76] the UK mobilized to keep its partners from accepting the U.S. invitation, so that the reciprocity rationale would be preserved.

The British strategy for resisting the U.S. initiative to offer a Portsmouth tour went beyond merely whipping the Netherlands into declining the invitation, but also to pushing the Netherlands to respond on behalf of the Troika, as the Netherlands was chairing the JC that year.[77] The fact that the negative reply came from the Netherlands, the most open country to cascade access during the

[73] Rooke to Wansink, Manley, and Schmidt-Küster, "Location of Plenary Meeting of Hexapartite Safeguards Project" (February 20, 1981), Attachment to Brown to Manley, TNA FCO 96/1464/25 (May 11, 1981).
[74] Fred Brown to Colin Budd, "The Hexapartite Safeguards Project (HSP)," TNA FCO 94/1464/34 (May 5, 1981).
[75] Brown to Manley, TNA FCO 96/1464/25 (May 11, 1981), 1.
[76] John. V. Granger to Frederick Brown, TNA FCO 94/1464/36 (May 13, 1981).
[77] Brown to Budd, TNA FCO 94/1464/34 (May 5, 1981); UK Fuel London to The Hague, Telegram No. 3, TNA FCO 96/1464/38 (May 19, 1981).

HSP, would perhaps give the United States second thoughts about whether it was worth offering the tour at all. It is unclear whether the Netherlands declined the tour, however, and plans for the tour, scheduled for July 17, 1981, remained in place.[78]

While some participants, especially the United States, took a more technical approach, developing safeguards technology for application in cascade areas, political wrangling by the Troika worked against attempts to facilitate the exchange of information, and to streamline the HSP's work. Meanwhile, the Troika's own endeavor to maintain solidarity created internal tensions—while the Netherlands was champing at the bit to conclude an Almelo FA that featured cascade access, the FRG was pulling in almost entirely the opposite direction, with the UK stuck somewhere in between, doing most of the leg work to prevent the Troika line from splitting apart completely. These dynamics continued through summer and fall 1981, up to the fourth HSP plenary meeting.[79] Although the Boekelo Understanding had eased tensions over the HSP's treatment of undeclared activities by this stage, the drafting process for the Troika's Team 4 paper was nevertheless a flashpoint between the three partners.

By early June 1981, the TSWG had produced a full draft of the Troika's Team 4 contribution, and had submitted it to the SOS.[80] The paper, in keeping with the TSWG's mandate from the February 18 SOS meeting, drew no conclusions about whether cascade access was necessary or not, and

[78] F. Brown to F. Bett et al., "Hexapartite Safeguards Project: Third Meeting 20-24 July 1981," TNA FCO 96/1464/53 (June 22, 1981).
[79] J.I. Smith, Action Items from Hexapartite Safeguards Project Second Plenary Meeting (March 27, 1981), attachment to J.I. Smith to R. Marsh, "Re: Hexapartite Safeguards Project," TNA FCO 96/1464/27 (March 27, 1981).
[80] "Troika Paper to Team 4" (June 5, 1981), attachment to J.A.B. Gresley to F. Brown, "Troika Paper to Team 4 of the Hexapartite Safeguards Project," TNA FCO 96/1464/44 (June 5, 1981).

merely presented the Troika's assessment of the safeguards value, potential security issues, and operations impacts of different types of access strategies. As stated by the TSWG chair, Blackwell Gresley, the Troika's Team 4 paper made "extensive use"[81] of the so-called 'Boekelo understanding,' making no explicit statements on how access strategies might address undeclared materials and equipment.

The June 1981 Troika Team 4 paper considered four possible access models: "once-off access," "limited access by agreement," "unannounced limited access," and "total unlimited access,"[82] elaborating on possible inspection activities under each regime. A summary of each concept, along with commentary, is given below.[83]

- Once-off access: For once-off access, the paper assumed that cascade areas in the facility would be examined shortly after its completion, after which these areas would be never visited again by inspectors, thus eliminating the possibility of the use of any instruments in the cascade area. The TSWG noted that inspectors could verify the absence of any bulk material storage areas in the cascade area, as well as any installed feed and withdrawal equipment. Inspectors could also verify physical containment of the cascade area, as well as evaluate the potential for cascade reconfigurations to be made. The former three activities would be vital for setting up a containment boundary around the cascade hall (presumably constituting some variant of a perimeter control system), while the latter activity would be very useful in conducting design information verification, by the

[81] Gresley to Brown (June 5, 1981).
[82] Ibid., 5.
[83] Ibid., 5–17.

TSWG's assessment. This access regime had been considered an option in the context of Euratom safeguards, as Euratom battled the Troika for cascade access at Almelo in 1972 and 1973, and at Capenhurst in the mid-1970s.

- Limited Access by Agreement: Under this model, the TSWG assumed that the frequency of cascade hall inspections would be limited to a certain number per year. A minimum notice period would apply to all cascade inspections, which the operator could use to screen sensitive (non-safeguards relevant) items from inspectors, although it was recognized that this time could also be used to conceal small containers of UF_6, as well as mobile feed and withdrawal carts. As the name suggests, while inspection activities would be limited to specific agreed measures, inspectors would be able to conduct both visual observation activities to verify the absence of undeclared or modified pipework, as well as verify containment of the cascade area, and even use seals on valves or flanges, if necessary. The TSWG also suggested direct cascade sampling (and subsequent destructive assay), along with the possible use of fixed radiation monitoring equipment and portable NDA equipment, although the Troika governments would later oppose the use of radiation detection instruments inside cascade halls. Although the paper does not specify the duration of the notice period, it is implied that it would be for an extended period of time – more than a few hours, or perhaps on the order of days, given that the 'unannounced limited access model' recognized that for practical reasons, a minimum of "one or two hours"[84] would be needed between inspectors appearing at the gate of a facility, and the inspectors entering the cascade hall. Without any technical motivation (or even reference to the

[84] Ibid., 13.

capacity of a plant), the TSWG stated, "[i]t should be possible to provide convincing evidence of the difficulty of modifying running plant [sic.], and the number of inspections considered to be necessary would probably be not more than four per year."[85] This reference to four cascade inspections per year appears to be the first time any Troika member quoted a specific frequency for inspections—and ultimately ended up being the lower limit for LFUA frequency in the agreed HSP approach, following a political compromise on LFUA frequency made between the United States and FRG at the end of the HSP.

- Unannounced Limited Access: This model is essentially identical to the 'limited access by agreement' model, except without notice periods for inspection. The motivation for totally unannounced access was to reduce chances that an operator could conceal evidence of facility misuse, at the cost of the operator not being able to secure sensitive information and equipment before the arrival of inspectors. This approach, in essence, is identical to the LFUA model that was ultimately agreed by the HSP, although the LFUA specifies a maximum notice period of 2 hours. The short duration of the 2-hour LFUA notice period, however, serves less as a notice period under the 'limited access by agreement' model, and more as a formalization of the time required for an operator to admit inspectors to a cascade hall. As noted in the Troika's paper, instantaneous access on demand would be functionally impossible. Although the paper does not elaborate on the 'one or two hours' estimate, one can imagine that inspectors, upon arriving at a facility, would need to undergo a security check (along with their equipment), a safety briefing, and a meeting with the operator to

[85] Ibid., 12.

discuss the inspection activities to be performed. Meanwhile, the operator would need to find qualified staff, who would be normally occupied with other duties, to escort the inspectors through the facility and cascade area.

- Total Unlimited Access: This regime would allow for an unlimited number of no-notice inspections of cascade halls, up to the centrifuge casings. Regarding visual observation activities, the TSWG concluded that unlimited visits would add essentially no benefit over the limited frequency models, as it was assumed that the agreed frequency for these models already took into account timeliness considerations for producing a significant quantity of over-enriched material. For the use of instrumentation, on the other hand, the TSWG noted that unlimited frequency access could facilitate the use of monitoring equipment requiring frequent maintenance, as did optical surveillance systems at the time. In conclusion, however, the TSWG assessed that total unlimited access would not be any more effective than the limited access models.

Of the four access regimes, the TSWG found that the unannounced limited access model provided the most safeguards value.[86]

Parts of the TSWG's draft of the Team 4 paper, despite its delicate treatment of undeclared feed and equipment, were unacceptable to the FRG. In particular, the West German government was troubled by language in the section on once-off access about the use of C/S at cascade hall boundaries for verifying the absence of movements of material into cascade halls, as well as the use of visual observation inside cascade halls for verifying the absence of feed and withdrawal

[86] Ibid., 18–19.

equipment.[87] To the C/S point, the paper stated, "the safeguards value of [visual observation to verify the absence of bulk material storage in cascade halls] would depend on there being a system of C/S control at the cascade hall boundary, to detect any attempt to introduce materials after the single inspection was completed."[88] Regarding the second point of objection, the offending language read, "[i]t may be possible to verify that there was no equipment for connecting mobile equipment to individual cascades. If this were not possible, a once-off inspection would not counter this diversion method."[89] Both of these points tacitly acknowledged the possible existence of undeclared feed. The FRG also objected to the inclusion of a separate Urenco paper as an appendix[90] that recognized the possibility of undeclared capacity. Meanwhile, the UK criticized a section of the paper that assessed the sensitivity of information that would be revealed to inspectors through the four different access regimes, from the TSWG's perspective. The TSWG and the Urenco shareholders had studied classification levels of cascade information that could be potentially revealed to inspectors, as well as the resulting security implications of doing so, but the Troika governments themselves had not yet come to agreement on this issue.

To paper over the lack of consensus on security issues, the UKDOE recommended replacing security/classification section with a "bland statement" declaring that the three governments were still evaluating the security implications of access and suggested that an SOS meeting be called to

[87] Ibid., 6; Boucsein to A.J. van Galen Last, "Troika-Paper to Team 4 of the HSP," TNA FCO 96/1464/48 (June 24, 1981).
[88] "Troika Paper to Team 4" (June 5, 1981), 6.
[89] Ibid.
[90] Urenco Limited, "Troika Operators – IAEA Euratom Technical Safeguards Meeting," UTN 1258.1, 1981, attachment to J.A.B. Gresley to F. Brown, "Troika Paper to Team 4 of the Hexapartite Safeguards Project," TNA FCO 96/1464/44 (June 5, 1981).

review the paper.[91] The FRG concurred with the UK's proposal.[92] Efforts to hold a meeting,[93] however, failed. Instead, the Dutch SOS Chairman, Aldert Jan van Galen Last, issued a telex stating that organizing a meeting "turned out to be impossible" and instead proposed a set of edits to the paper, based on the UK and FRG comments.[94] A footnote was added to the language that the FRG found objectionable, stating that the assumption that inspectors were to verify the absence of undeclared material did not "enjoy universal support." The British suggestion to redact the section on security classification was also accepted. In closing, van Galen Last requested that any further comments on the paper to be made via telephone, by 5 PM the following day, June 25.[95] A second telex, sent by van Galen Last, set a final deadline for comments at 3 PM on June 29.[96]

The West German government, nevertheless, reiterated its request on June 29 that a face-to-face meeting be held on the Team 4 paper.[97] The Dutch government did not act on this message. In a telex sent the following day, van Galen Last reported that the FRG's message was received at 5:10 PM on June 29, just over two hours after the deadline. Since the 3 PM deadline had passed, van Galen Last wrote, "it had to be concluded that the compromise solution proposed by the chairman of the SOS had been accepted by the German side," and the Team 4 paper, with the Dutch amendments, was immediately distributed to all contact points in HSP States.[98] In doing this, the

[91] Brown to A.J. van Galen Last, "Joint Committee Sub-Group on Safeguards," TNA FCO 96/1464/46 (June 15, 1981).
[92] Boucsein to A.J. van Galen Last, TNA FCO 96/1464/48 (June 24, 1981).
[93] Netherlands Ministry of Foreign Affairs to Brown, "Joint Committee Sub-Group on Safeguards," TNA FCO 96/1464/54 (June 17, 1981).
[94] A.J. van Galen Last to Brown and Boucsein, "Joint Committee Sub-Group on Safeguards (SOS)," TNA FCO 96/1464/55 (June 24, 1981).
[95] van Galen Last to Brown (June 24, 1981).
[96] Referenced in A.J. van Galen Last to Boucsein, "Troika Paper for HSP Team 4," TNA FCO 96/1464/50 (June 30, 1981).
[97] Boucsein to A.J. van Galen Last, "Troika-Paper to Team 4 of the HSP," TNA FCO 96/1464/52 (June 29, 1981).
[98] A.J. van Galen Last to Boucsein, TNA FCO 96/1464/50 (June 30, 1981).

Dutch government unilaterally precluded any further substantive discussion of the content of the Team 4 paper within the Troika, and also compelled the FRG not to dispute any material in the paper during subsequent HSP meeting.

Comparing the U.S. and Troika Team 4 Papers

The United States also produced a Team 4 paper, for discussion at the third HSP plenary meeting.[99] Unlike the Europeans, who left the drafting process for their Team 4 paper to the facility operators, the U.S. Team 4 paper was drafted by national laboratory personnel. While the European paper first defined four levels of access and described possible activities that could be carried out under each level, the U.S. paper took various technical measures (i.e. NDA measures) as a starting point and used combinations of them as a basis for defining possible access regimes—essentially the reverse of the TSWG's logic. As a result, the U.S. paper defined levels of access in terms of the types of measurements available to inspectors, and not as a function of frequency and notice periods, as the Troika had done.

A rather byzantine process was used by the U.S. paper's authors to craft the ten strategies that the paper ultimately suggested. The U.S. Team 4 drafting group selected five stationary instruments and seven portable instruments for use inside cascades, as listed in Table 6-2. Each type of instrument, the paper argued, could be used in five different locations: the cascade itself, cascade utility bays, crane bays, the roof of the cascade hall, and at the cascade wall ports. At the same

[99] D.M. Gordon et al., "Selection of Potential IAEA Inspection Strategies Involving Cascade Access at the Portsmouth Gas Centrifuge Enrichment Plant (GCEP)," K/OA-4955 (Oak Ridge, TN: Union Carbide Nuclear Division, April 13, 1981), obtained by the author via Freedom of Information Act Request #OSTI-2017-00114-F.

time, each device could be used to confirm the absence of HEU in the cascade hall, or the "completeness and correctness" of material inventory declarations for the plant.[100] With 2 safeguards objectives and 5 locations, each instrument could be applied in 10 different use cases. Furthermore, the study considered that stationary radiation monitors could be installed, maintained and verified under three different regimes, as listed below:[101]

- Installed, maintained, and verified by the inspectorate
- Installed by the inspectorate, maintained by the facility operator, and remotely verified by the inspectorate
- Installed by the facility, maintained by the facility, and remotely verified by the inspectorate.

Portable radiation monitors could be used in two ways:[102]

- Used directly by the inspectorate
- Operated by the facility (with monitors under seal), and remotely verified by the inspectorate.

The 3 implementation regimes for the 5 stationary safeguards devices, each with 10 use cases, yielded 150 potential use cases. The 7 types of portable instrumentation, each with 10 use cases and 2 implementation regimes, yielded 140 use cases. Thus, a total of 290 use cases were evaluated for the U.S. technologies.

[100] Ibid., 17.
[101] Ibid., 18.
[102] Ibid., 19.

Table 6-2: List of measurement instruments proposed in U.S. Team 4 Paper for use in cascade access. Source: D.M. Gordon et al, "Selection of Potential IAEA Inspection Strategies…," 7.

Stationary Radiation Monitors	Portable Radiation Monitors
• Neutron Monitor Array • Gamma Monitor Array • Gamma Monitor for Cascade Pipes • Collimated, High-Energy Gamma Monitor • Collimated, Low-Energy Gamma Monitor	• Gamma Monitor for Centrifuges • Gamma Monitor for Cascade Pipes • Gamma Monitor for Area Measurements • Neutron Monitor for Area Measurements • Collimated, High-Energy Gamma Monitor • Collimated, Low-Energy Gamma Monitor • UF_6 trap monitor

Of the 290 use cases, 84 were deemed to be useful for either of the two safeguards objectives discussed above. These 84 use cases were boiled down into 14 "preliminary" strategies, each using a certain combination of either stationary or portable radiation monitors in a given location. For example, the first preliminary strategy called for the use of all five types of stationary radiation monitors in the cascade and utility bays, all of which would be installed, maintained and verified by the inspectorate.[103] Finally, these 14 preliminary strategies were distilled into 10 "candidate" strategies, featuring combinations of stationary and portable radiation monitors. Along with each candidate strategy, a cascade access frequency was estimated. The 10 inspection strategies proposed by the United States are shown in Table 6-3. Of the 10 inspection strategies, the ultimately agreed LFUA method was most similar to strategy 10, although with equipment only used in cascade area (not in utility bays) and, with an emphasis at first on the use of portable equipment.

[103] D.M. Gordon et al. (April 13, 1981), 21.

Table 6-3: "Examples of Candidate International Inspection Strategies for the GCEP Process Buildings," Table 9 in D.M. Gordon et al, "Selection of Potential IAEA Inspection Strategies…," 22.

Strategy	Estimated Cascade Access Frequency*
1. Stationary radiation monitors installed by the inspectorate in the cascade and utility bays	Quarterly to Annually (remote verification might be required)
2. Stationary radiation monitors installed by the inspectorate in the crane bays	Quarterly to Annually (remote verification might be required)
3. Rooftop radiation monitors	**
4. Gamma monitors installed in building wall ports	(CCTV viewing through the ports may be required)**
5. Stationary radiation monitors installed by the facility or portable instruments used by the facility in the cascade and utility bays with location verification devices	(location verification device is required)**
6. Stationary radiation monitors installed by the facility or portable instruments used by the facility in the crane bays with CCTV verification from the wall ports	(CCTV viewing of upper portion of cascade is required)**
7. Portable instruments used by the inspector in the cascade and utility bays	Weekly to Monthly
8. Portable instruments used by the inspector from the overhead crane	Weekly to Monthly
9. Stationary monitors and portable instruments installed, verified, and used by the inspectorate in the crane bays	Quarterly
10. Stationary monitors and portable instruments installed, verified, and used by the inspectorate in the cascade and utility bays	Quarterly

* Actual frequencies will depend on a number of variables, including effectiveness of remote verification, instrument reliability, relative effectiveness of stationary and portable monitors, access delay, and probability of detection required.

**Strategy emphasizes a verification approach which requires little or no internal access during its implementation. However, access may be required at other times in order to confirm that the strategy's assumptions are, or remain, valid. The need timing and frequency of internal access is under investigation.

In comparing the U.S. and European approaches to the Team 4 papers, while it is clear that although the two sides drafted their papers on the basis of technical analysis, the methodologies used for each paper were entirely different. The Troika paper focused on operational parameters

of access—mainly frequency and notice periods. The American paper, on the other hand, took a technology-driven approach. It can be argued that the two papers were in some ways complementary, in that the U.S. Team 4 work presented concrete NDA concepts and systems that could be applied to the more nebulous concepts for instrumentation in the Troika paper. Going the other way, the Troika paper discussed the question of whether to implement unannounced or announced inspections, along with inspection notice periods, which the U.S. paper hardly brought up at all. At the same time, however, there also were few concepts that were shared between the two papers that could provide any common ground for discussion at the HSP. While cascade access frequency was brought up in both papers, the U.S. paper conceived frequency as a parameter driven by the capabilities of installed NDA instrumentation, while the Troika paper proposed quarterly cascade access on the basis of plant characteristics. The possible utility of visual observation during cascade inspections (perhaps reflective of the more 'transparent' and repetitive design of Urenco's cascade piping) is treated with far more consideration in the Troika paper, versus the U.S. paper. With these stark differences in mind, it is not surprising that the 3rd HSP plenary failed to make much leeway in addressing how to approach cascade access.

The Third HSP Plenary Meeting, Washington DC, July 20–24, 1981

The 3rd HSP plenary session, held in July 1981 in Germantown, Maryland (in the Washington, DC area), was the final meeting before the HSP's one-year review, which would take place in November 1981 in Tokyo. By the time of the Washington plenary, the IAEA (as well as the Dutch government) had begun to grow anxious for concrete progress—at this point, no field testing of equipment had taken place, and discussions during the HSP plenary sessions had not gone far

beyond political posturing. At the meeting, Adolf von Baeckmann, the IAEA's HSP lead, delivered a message on behalf of the Deputy Director General for Safeguards, Hans Gruemm, imploring the HSP participants not to use the forum to discuss interpretations of INFCIRC/153. Gruemm also wrote that the HSP's work had been too theoretical, and that practical demonstrations were necessary before any control methods could be used in facilities.[104] Nevertheless, despite Gruemm's concerns, the HSP continued as it had done before.

Although the portion of the meeting dealing with Team 4's work proved to be most politically charged, some controversy arose during discussions of other teams' work. Team 2 had met in Marlow, England the week before to put together a common progress report on available C/S measures to be used if the HSP were to agree to implement a non-access approach.[105] At the plenary, both the United States and the IAEA criticized the report. The IAEA, represented by von Baeckmann, expressed concern about the practicality of control concepts that were contingent upon the availability of devices and instrumentation that were not yet verifiable, echoing the Troika's criticism of the U.S. perimeter safeguards concept of the 1970s. For the IAEA, independent verifiability, reliability, credibility, and non-spoofability of C/S devices was paramount—and these qualities had not yet been proven for several of the technologies under consideration.[106] With a certain degree of irony (with respect to the developmental state of proposed perimeter safeguards technologies at the time that concept had been proposed), the

[104] Rüdiger Gerstler, "Multilaterales Kooperationsprogramm "Kontrollmaßnahmen für GUZ-Anlagen" – Hexapartite Safeguards Project (HSP): 3. Sitzung vom 20. – 24. Juli 1981 in Germantown, Maryland (USA). Zusammenfassender Vermerk über den Sitzungsverlauf," BArch, B 196/110542 (August 4, 1981), 8.
[105] Ibid., 2–3.
[106] Ibid., 2–3. For a list of C/S devices under consideration, see "Containment and Surveillance: A Progress Report from Team 2" (March 18, 1981), Appendix VII to "Second Meeting of the Hexapartite Safeguards Project: Chairman's Notes," TNA FCO 94/1464 (March 20, 1981).

United States also argued that the report had been too optimistic in estimating the developmental maturity of the some of the C/S devices under consideration. Nevertheless, the United States also displayed annoyance with the IAEA, which refused to discuss its experience to date with implementing C/S measures at Almelo with currently available devices, for safeguards confidentiality reasons.[107]

The Team 3 report on materials accountancy techniques and methods, which like the Team 2 report was presented as a common volume, also faced similar criticism from the IAEA. This report had been based primarily on the experiences of Urenco, the only commercial GCEP operator that existed at the time. The IAEA argued, however, that the report portrayed a far too optimistic picture of currently available materials accountancy measures. It is possible, as the German account of the meeting notes,[108] that the IAEA may have been overdramatizing problems with C/S and materials accountancy methods and devices, in order to strengthen the case for cascade access down the road. This comment itself, however, belies a certain degree of distrust and lack of good faith within the German delegation towards the IAEA, reflective of the overall mood of the meeting.

Discussion of the Team 4 reports, however, caused the most strife. Four reports had been submitted: one each from the Troika, the United States, Japan, and Australia, although the FRG delegation questioned the usefulness of the Australian report, as Australia had no experience with operating a commercial facility, the subject of HSP-type safeguards.[109] A German account of the

[107] Gerstler, "Multilaterales Kooperationsprogram…" BArch, B 196/110542 (August 4, 1981), 3.
[108] Ibid., 4.
[109] Ibid., 6. Gerstler also reports that Australia's report had been drafted under U.S. pressure. This is somewhat consistent with a note in the 2nd HSP Plenary Chairman's Note, in which Australia was instructed to prepare a Team 4 paper, despite it being noted in the meeting that Australia was only operating an R&D

meeting records that both the Troika and the United States directed criticism at each other's reports, while the IAEA took issue with both papers. The FRG, for example, criticized the U.S. paper for being too theoretical, and for not going into considering any practical aspects of cascade access, while the IAEA was frustrated that the U.S. concept was based on measurement devices that it knew nothing about.[110] The safeguards instruments described in the U.S. paper had been developed for domestic safeguards at the Portsmouth GCEP, and had never been used before by the IAEA, leaving the IAEA to question issues including the availability of the technology, whether measurements could be spoofed, and measurement sensitivities—similar to the problems the IAEA identified with the Team 2 paper.[111] Meanwhile, the United States criticized the Troika paper for being imbalanced and lacking transparency,[112] presumably over methodologies for determining critical elements like the Troika's proposed quarterly access frequency in the limited cases. The FRG delegation was dismayed to hear that the U.S. also disputed the Troika position that effective and efficient safeguards could be carried out without cascade access (as the Troika illustrated for the once-off access case).[113] The IAEA, as it had done for the U.S. paper, complained that the Troika's "conclusions"[114] were too optimistic, referring most likely to the effectiveness of the safeguards measures that the Troika proposed under each access model. The Japanese paper, a systems study analyzing the relationship between safeguards effectiveness and various inspection activities, on the other hand, seems to have garnered few comments.[115]

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facility at the time. The HSP participants, in fact, agreed at the 3rd plenary that the HSP safeguards approach would only be applicable to commercial enrichment facilities.

[110] Ibid., 5.

[111] Ibid. Original German: "Fragen der Verifizierung, Verfügbarkeit, Fälschungssicherheit, Ansprechempfindlichkeit seien… noch nich gelöst."

[112] Ibid. Original German, "Am Troika-Entwurf bemängelten die US-Vertreter besonders die Unausgewogenheit und fehlende Transparenz."

[113] Ibid.

[114] Ibid. Original German: "Schlußfolgerungen"

[115] Ibid.

During these discussions, the United States reported to the UK that "they found the FRG attitude non-productive."[116] Throughout the 3rd HSP plenary, the FRG continued to resist any hints of the possibility of undeclared feed and capacity being considered. Clearly, the FRG's sensitivity to this issue bordered on the extreme, given that the Troika Team 4 paper, which had been drafted explicitly with the Boekelo Understanding in mind, still offended the FRG by only making the slightest references to 'undeclared' issues. U.S. delegates met with Rüdiger Gerstler, the head of the FRG delegation, to try softening the German position, but failed to make progress.[117] As the end of the HSP's first year approached, the FRG position still posed a serious obstacle to agreement on an access concept.

Towards the end of the third plenary, the FRG delegation would become yet more irritated, as the U.S. delegation took the initiative to form a sub-committee to draft a progress report on the HSP's work to date, in preparation for the 4th plenary in Tokyo.[118] The U.S. chairman, Len Brenner of the U.S. Department of Energy (USDOE), however, chose a Dutch national, Jan Harry, to chair the group without consultation of either the UK or the FRG.[119] Given the known Dutch position on cascade access, this decision pained the FRG delegation. According to a British report, Gerstler "was extremely upset at this situation," and threatened to raise the issue at the JC.[120]

[116] F. Brown to N.J. Thorpe, "The Hexapartite Safeguards Project: Troika Considerations," TNA FCO 96/1465/63 (August 6, 1981), 1.
[117] Ibid.
[118] Gerstler, "Multilaterales Kooperationsprogramm…" BArch, B 196/110542 (August 4, 1981), 6.
[119] F. Brown to N.J. Thorpe, "The Hexapartite Safeguards Project: Troika Considerations," TNA FCO 96/1465/63 (August 6, 1981), 1.
[120] Ibid.

To top off the Troika's woes, a leak of the original Troika Team 4 paper also took place during the 3rd HSP plenary. While meeting with a Japanese HSP delegate, Blackwell Gresley discovered that the Japanese representative had somehow obtained the TSWG's original draft of the Team 4 paper, without the disclaimer footnote inserted by the Netherlands, and containing the TSWG's detailed discussion on security classification issues, instead of the 'sanitized' version that had been distributed by the Netherlands. Upon being asked by Gresley where he obtained the paper, the Japanese delegate stated that the paper had been passed to him when he arrived at his hotel in the United States.[121] Clearly, the unedited paper had been leaked from somewhere within the Troika, with the result that other HSP participants were more acutely aware of ongoing disputes between the three States. Perhaps the paper had been leaked by mistake—or perhaps it had been leaked maliciously, to draw attention among other HSP participants to the fact that the Troika Team 4 paper, which favored unannounced limited access, enjoyed less than universal support than it seemed.

Preparing for the 4th HSP Plenary

By the end of the 3rd HSP plenary meeting, a successful conclusion to the exercise was far from certain. Over the summer and fall of 1981, the Dutch government became increasingly frustrated with UK and FRG resistance to facility access, and the FRG's persistent stonewalling on the issue of undeclared activities and material. Shortly before the fourth HSP plenary, which was to be held in Tokyo on November 4-13, 1981, the UK and FRG became concerned about Dutch threats to unilaterally instruct Euratom to conclude an FA for the Almelo GCEP, bypassing JC oversight

[121] Wilfred Rooke to C.L. Berke, Letter, PA AA, B 72 (ZA)/129440 (September 3, 1981).

entirely, and in violation of the Treaty of Almelo.[122] In late October 1981, the Joint Nuclear Unit in the UK Foreign & Commonwealth Office (UKFCO) consulted an in-house legal adviser as to whether the Treaty of Almelo would prevent the Netherlands from acting unilaterally in this regard.[123] Although the UKFCO legal counselor reported that unilateral Dutch action would be illegal,[124] this observation only gave meager comfort to UK government officials. As the Troika's disagreement over the HSP dragged on over 1981, parallel concerns had been mounting that the Netherlands would withdraw from the Treaty of Almelo altogether, which had recently become legally possible.[125] The Dutch Labour Party, which joined the Dutch government following a general election in May 1981, supported closure of the Almelo GCEP.[126]

At the same time, the IAEA's frustration with the HSP's progress reached a breaking point. While the first year of the HSP mainly been occupied with theoretical questions concerning the necessity of various degrees of cascade access, the IAEA did not view this as the HSP's primary goal (one must consider of course, that the IAEA's position from the beginning was that cascade access was necessary). The IAEA had hoped that the HSP would focus mainly on demonstration of devices and instruments, in order to establish a technical basis for a GCEP safeguards approach. This had

[122] Brown to Kelly, TNA FCO 96/1465/83 (October 30, 1981).
[123] J.W. Thorp to A.D. Watts, "The Treaty of Almelo and Negotiation of Subsidiary Arrangements," TNA FCO 96/1465/74 (October 27, 1981).
[124] A.D. Watts to J.W. Thorp, "The Treaty of Almelo and Inspections, TNA FCO 96/1465/76 (November 2, 1981).
[125] Article XV of the Treaty of Almelo allows any party to withdraw from the agreement with a 1-year notice period, after the agreement has been in force for ten years.
[126] In 1981, the UKFCO maintained a file on potential ramifications of Dutch withdrawal from the Treaty of Almelo. See *URENCO: extension of the Treaty of Almelo 1970; possible withdrawal of the Netherlands*, TNA FCO 96/1406 (1981).

not happened, and by late October 1981, the IAEA had threatened to pull out of the HSP altogether if political discussions were to continue.[127]

The crux of the dispute still lay in the question of whether to consider undeclared material and equipment (and thus whether inspectorates should have cascade access), between the FRG and Japan on one side, and the United States, Netherlands and Australia on the other. By fall 1981, the UK moved towards a more neutral position, favoring limited cascade access, to prevent the Netherlands from acting unilaterally.[128] Meanwhile, the United States had become more emphatic about the need to verify the absence of undeclared feed and capacity under INFCIRC/153. The recent June 1981 bombing of Iraq's Osirak reactor demonstrated, from a U.S. perspective, that the international safeguards system did not provide sufficient assurances to States that felt threatened by other States' nuclear fuel cycle activities. Because the HSP would set a precedent for GCEP safeguards in years to come, the United States argued that any approach agreed by the HSP would also have to be credible if applied at enrichment plants in states of greater proliferation concern at the time, such as Pakistan, South Africa and Brazil.[129] Credibility of such a GCEP safeguards approach would be contingent upon IAEA inspector access to cascade areas.[130]

West German representatives recognized the increasing isolation of the FRG in the HSP, now that the United States was increasingly favoring access over non-access, and perceived that the United

[127] Rüdiger Gerstler, "Multilaterales Kooperationsprogramm Kontrollmaßnahmen für GUZ-Anlagen (Hexapartite Safeguards Project: Sachstandsbericht über den derzeitigen Stand der internationalen Diskussion und Vorschläge bezüglich weiterer Vorgehensweise," BArch, B 196/110542 (October 29, 1981), 4.
[128] Ibid., 4.
[129] Ibid., 2–3.
[130] Ibid., 3.

States was pressuring the other participants to ostracize the FRG, because of its position on the undeclared issue.[131] Nevertheless, going into the 4th HSP plenary, FRG chose to stick with the same line it had taken up to that point. In preparation, Rüdiger Gerstler drafted an extensive justification for the FRG's line. Fundamentally, the FRG's interest was in the development of an implementable safeguards approach, as opposed to an approach that the FRG viewed as overly perfectionistic. From the FRG's point of view, if the existence of undeclared material and equipment was to be "presumed,"[132] it would be impossible to craft a practical safeguards approach, notwithstanding its position on the applicability of INFCIRC/153 to undeclared material. Gerstler wrote:

> "A control system that presumes the existence of unknown materials that can be introduced at any time to any location in the nuclear fuel cycle cannot be based on material balance. Material balance depends on the principle of conservation of mass, and the assumption of secret and in principle infinite sources drives this system to the point of absurdity. The result is the following perspective: the assumption of undeclared materials means that the closure of a material balance area is only meaningful when a very extensive and correspondingly expensive C/S-System ("Christmas Tree") isolates the relevant material balance area, so that the introduction and removal of undeclared material is made impossible."[133]

[131] Ibid., 2.

[132] FRG policy documents from the HSP often used the word "voraussetzen" in the context of the attitude of other States and inspectorates towards the undeclared issue, which can mean to hypothesize, postulate, or presume, as well as "Unterstellung," which translates to "assumption." For the FRG, considering the possible existence of undeclared material and equipment essentially meant assuming its existence, prior to collection of sufficient evidence proving the contrary. Ibid., 5.

[133] Ibid., 5–6. Original German: "Ein Kontrollsystem, daß die Existenz unbekannten Materials voraussetzt, das zudem zu jeder Zeit an jeder beliebigen Stelle in den Brennstoffkreislauf- eingebracht werden könnte, kann im übrigen nicht mehr auf Materialbilanzierung basieren. Materialbilanizierung beruht im Prinzip auf Massenerhaltung, die Unterstellung von verborgenen im Prinzip unerschöpflichen Quellen führt dieses System ad adsurdum [sic.]. Hinzu kommt noch folgender Gesichtspunkt: die Unterstellung undeklarierten Materials hätte zur Folge, daß das Schließen einer Materialbilanzzone nur dann sinnvoll wäre, wenn ein sehr ausgedehntes und entprechend teures C/S-System ("Christbaum") die betreffende Materialbilanzzone effektiv von der umgebung isoliert, so daß ein Herein- und Herausbringen von undeklariertem Material unmöglich gemacht wird."

Of course, in addition its concern over overelaborate C/S measures, the FRG was still worried about potential proliferation risks associated with cascade access. In inter-Troika discussions on the risk of revealing classified information through cascade access that took place after the drafting of the Team 4 paper, the FRG had argued that information classified up to 'Secret' could be revealed, disagreeing with the UK, who believed that information up to 'Confidential' would be disclosed if inspectors were granted unlimited access, and the Netherlands, which believed that only the 'Restricted' level would be breached.[134] During informal U.S.-Troika talks in Vienna, Gerstler presented a draft statement summarizing the three Troika positions, to be included in a Troika HSP report, to Joerg Menzel, the U.S. HSP delegation head. In response, Menzel pointed out that if information classified 'Secret' could be revealed via cascade access, then the Troika was already in breach of security regulations, and that quadripartite discussions would need to take place to address the situation.[135] This threat successfully deterred the FRG from bringing up its assessment of possible classified information leaks in the HSP, and in the October 1981 FRG position brief,[136] the issue of classified information is not raised in substantive detail.

Nevertheless, the FRG still maintained its position that safeguards in NPT Non-Nuclear Weapon States, which made a commitment to uphold their commitment to nonproliferation by submitting to comprehensive safeguards, should be considered differently to safeguards in the territories of non-NPT parties, which presented a greater proliferation concern at the time.[137] If anything, the FRG argued, the presence of undeclared material should only be viewed as plausible in non-NPT

[134] Brown to Kelly, TNA FCO 96/1465/83 (October 30, 1981), 4.
[135] Ibid.
[136] Rüdiger Gerstler, "Multilaterales Kooperationsprogramm…," BArch, B 196/110542 (October 29, 1981).
[137] Ibid., 5.

States with piecemeal INFCIRC/66-type agreements, and not in States under comprehensive safeguards.[138]

Despite the FRG's perennial allergy to the undeclared issue and to cascade access, the October 1981 FRG brief, for the first time, discussed the potential advantages of limited cascade access. In doing so, the paper recognized that if undeclared capacity or material were assumed, it could be possible to eliminate the need for a complicated C/S system, visual inspection could be used to verify that operations were as declared, simplifying DIV activities. Furthermore, the paper stated that proliferation risks could be minimized via administrative measures under limited access, to conceal sensitive information from inspectors.[139] In addition, the FRG recognized that it would be unable to resist limited access, if it were to be proven to have cost advantages and involve simpler verification measures. The HSP had not yet reached this point, however, thus allowing the FRG to favor non-access for the time being, but these statements—and for the first time, a willingness to consider cascade access as a possibility—marked a significant change in attitude on the part of the FRG delegation. Of course, given the FRG's political objective of excluding undeclared material and equipment from GCEP safeguards considerations, the FRG paper still noted the tactical need to abide by its non-access position,[140] in order to retain bargaining leverage as specific limited access measures were negotiated.[141]

[138] Ibid., 8.
[139] Ibid., 7.
[140] Ibid., 9.
[141] Ibid. Original German: "Schon aus taktischen Erwägungen ist es vielmehr wichtig, daß wir bis auf weiteres bei unserer bisherigen Linie (auch Durchspielen des Non-Access-Modells) bleiben.

By contrast, the Netherlands was close to losing patience with its partners, and the common Troika line was under threat (pending that the Netherlands remained in the HSP, which was perhaps not to be taken for granted in the first place). Under threat of Dutch unilateral action and abrogation of the Treaty of Almelo, the UK government made a determined effort to maintain a unified Troika line at the Tokyo HSP meeting. This effort, however, failed disastrously. The evening prior to a JC meeting held on November 3, 1981 (at which time key members of the Troika's HSP delegations were already in or en route to Tokyo), a British JC delegate met with Dutch and German officials over drinks, in an attempt to bridge gaps in the three governments' positions, in preparation for a discussion of the Troika's HSP line the next day. Encouraged by this conversation, the UK subsequently tabled a position paper[142] at the JC meeting that had not been reviewed by the FRG or the Dutch delegations.[143] The paper, intended as a compromise between the Dutch and German positions, stated that both the access and non-access regimes were to be studied objectively by the three States. However, the paper also stated that safeguards activities applicable to plants in NPT states "would not necessarily be applicable in a non-NPT country,"[144] giving credence to the FRG's position that verification of the absence of undeclared activities in NPT Non-Nuclear Weapon States (NNWS) was extraneous to safeguards, overlooking the Boekelo understanding. This statement inflamed the Dutch delegation. Furthermore, Dutch representatives were offended that the UK tabled its paper at the last minute before the Tokyo

[142] "Guidelines for experts of Urenco-countries at HSP-meetings," PA AA, B 72 (ZA)/129441 (November 3, 1981).
[143] D.K. Haskell to Gilmore, "The Hexapartite Safeguards Project (HSP)," TNA FCO 96/1465/86 (November 16, 1981).
[144] Guidelines for experts of Urenco-countries…," PA AA, B 72 (ZA)/129441 (November 3, 1981). The underlying assumption behind the FRG position was that NPT NNWS, by virtue of them being NPT signatories, would not undertake undeclared activities.

HSP, and without any prior notice.[145] Bob Wansink, still chairing the JC at that time, refused to bring the paper to discussion. No agreement was made on the Troika's line for the imminent HSP meeting, and subsequently, an antagonistic exchange took place between the three delegations. The German delegation repeatedly called on the Dutch to comment on the paper's statement on safeguards in NPT versus non-NPT NNWS, which the Dutch refused to do.[146] While the official JC minutes note that Peter Kelly "deplored the fact that the Chairman was not prepared to discuss this matter in substance,"[147] British internal records indicate, however, that harsher words were exchanged. On a copy of minutes for internal use kept by the British delegation, a handwritten note states, "[n]ot a good meeting, because of poor Dutch chairmanship and an awful row over HSP."[148] Exasperation is evident in the tone of a telegram from Kelly, who tabled the paper in The Hague, to Fred Brown, who had already flown to Tokyo. Kelly wrote,

> "[The Dutch] could not, nor would not, see the point that the Troika disunity on safeguarding was potentially on public display at Tokyo, and might damage our commercial interest with the Australians and others. They also maintained that the safeguards experts should be left to complete their job and that only at the end of the exercise would the Joint Committee need to take a decision. This second argument had a hollow ring because the Dutch expert is a foreign ministry official without technical qualification and has apparently been reporting to his superiors in a similar sense to yourself."[149]

After this meeting, each Troika State issued its own set of instructions to its HSP delegation, and the UKFCO warned the UK HSP delegation that it would face the task of "papering over the large

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[145] "Minutes of the meeting of the Joint Committee held at Almelo on Tuesday, 3 November 1981," PA AA, B 72 (ZA)/129440 (November 3, 1981).
[146] UK FCO to Embassy Tokyo, Telegram No. 497, TNA FCO 96/1465/79 (November 5, 1981), 1.
[147] "Minutes of the meeting of the Joint Committee…," PA AA, B 72 (ZA)/129440 (November 3, 1981).
[148] N. Thorpe to Fullerton, "Joint Committee Meeting: Almelo 3 November," TNA FCO 96/1402/30 (November 12, 1981).
[149] UK FCO to Embassy Tokyo, TNA FCO 96/1465/79 (November 5, 1981), 1–2.

cracks in the Troika position."[150] Meanwhile, the UK faced the task of repairing relationships that had been harmed through this episode. Even a month after the JC meeting (and the Tokyo HSP plenary) had taken place, the UK Embassy in The Hague was still pressing the UKFCO on the need to make amends:

> "[T]he behaviour of one member of the UK delegation at the Almelo meeting has left a number of bruises here. Wansink, Kruyt and Terwisscha all ended the meeting in a state of great irritation, and even the normally equable Aldert Jan [van Galen Last] is clearly smarting somewhat over the outright criticism of the Netherlands presidency's failure to manage certain aspects of Urenco business more effectively. I fully understand there was irritation on our side as well… I would only say that as seen from here a real effort needs to be made to repair the damage."[151]

Nevertheless, amidst the tension during the run-up to the 4th HSP plenary, some progress was made. In October 1981, the UK initiated a three-month "safeguards development and evaluation programme"[152] with the IAEA and Euratom at the Capenhurst E21 demonstration facility, addressing the IAEA's concerns about a lack of practical work under the HSP. At the kickoff meeting, the UK exhibited some of the safeguards equipment that it had been developing under its IAEA Member State Support Programme (UK SP), which included a system for monitoring uranium and uranium-235 in the chemical traps at Capenhurst, an on-line enrichment meter for gaseous UF_6, and portal monitors for personnel and for packages entering and leaving the cascade area.[153] Consistent with the Troika position at the time, inspectors were not to be given access to cascade areas. However, the UK had drafted a detailed plan for the program, whose timeline is summarized in Figure 6-1.[154] The project would begin with familiarization visits, during which

[150] Ibid., 2.
[151] C.R. Budd to J.W. Thorp, Teleletter, TNA FCO 96/1465/103 (December 14, 1981), 1.
[152] F. Brown, "Note for the Record: IAEA and Euratom Visit to Capenhurst 19–21 October 1981," TNA FCO 96/1465/72 (October 28, 1981).
[153] Ibid.
[154] British Nuclear Fuels Limited, "Proposal for a Collaborative Safeguards Demonstration and Evaluation Programme at Capenhurst" (1981), attachment to ibid.

inspectors would be given plant drawings, introduced to the plant's accounting procedures, and shown typical operations at the plant, including the movement of UF_6 cylinders between storage and process areas, emplacement and removal of UF_6 cylinders from feed and withdrawal cells, transfer of UF_6 from desublimers into withdrawal cells, and cylinder weighing and sampling operations.[155] Next would come a demonstration of material accountancy techniques used by the facility's operator, including calibration of accountancy scales, the use of on-line load cells, enrichment assay techniques, holdup measurements and waste measurements.[156] Inspector measurement techniques would be simultaneously demonstrated, including portable weighing devices, the use of seals, NDA on UF_6 product cylinders, as well as the system developed by the UK SP for monitoring chemical traps. After a review of the assurance these techniques would provide (relative to inspection effort), a full physical inventory verification would take place, as well as a "rapid physical inventory" that could be used to address any off-normal safeguards indicators.[157] Another review would take place after this stage to assess the accuracy of the facility operator's material balance, before moving to the final phase, which would involve studying the use of containment and surveillance at the boundary of the cascade area. Inspectors were to be given drawings showing the locations of cascade areas in E21, along with each penetration into the cascade hall and its purpose. The inspectors would then be tasked with examining the credibility of diversion paths by tracing pipework and verifying that non-nuclear service pipes could not be used to carry UF_6. Testing of surveillance on cascade hall portals and ventilators would also be conducted.[158]

[155] Ibid., 2.
[156] Ibid., 4.
[157] Ibid., 5–6.
[158] Ibid., 7–9.

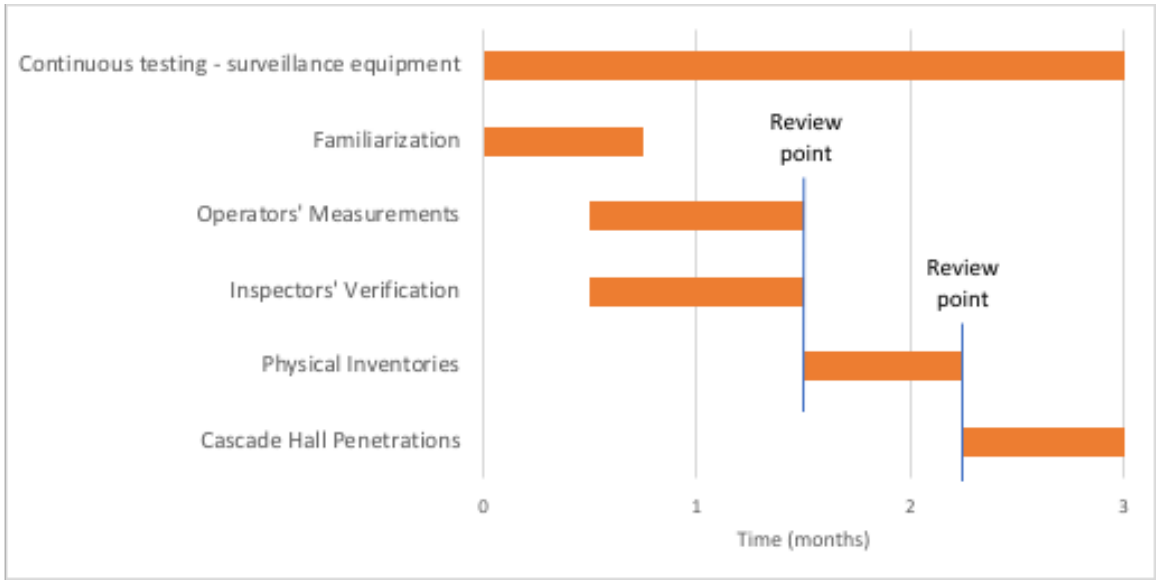

Figure 6-1: Gantt Chart for the UK-IAEA-Euratom Safeguards Demonstration and Evaluation Programme. Adapted from: British Nuclear Fuels Limited, "Proposal for a Collaborative Safeguards Demonstration and Evaluation Programme at Capenhurst" (1981), 10, attachment to F. Brown, "Note for the Record: IAEA and Euratom Visit to Capenhurst 19–21 October 1981," TNA FCO 96/1465/72 (October 28, 1981).

The UK-IAEA-Euratom program at Capenhurst came at a critical time during the HSP, just as the IAEA's frustration with the HSP's progress was reaching boiling point, ahead of the one-year review meeting. The UK showed remarkable flexibility in facilitating the program, even allowing IAEA inspectors from countries that the UK Government deemed sensitive, including Bulgaria, South Africa, and Czechoslovakia, to take part.[159] The duration of the effort was also chosen so that results of the project could be reported at the 5th HSP plenary, to be held in Sydney, Australia in March 1982.[160] In sum, the Capenhurst safeguards demonstration and evaluation program could not have come at a better time.

[159] D.R. Horsley to J.D. Fitzgerald, "Collaborative Safeguards Demonstration Programme at Capenhurst," TNA FCO 96/1465/96 (November 30, 1981); S.M. Williams to J. Fitzgerald, "Collaborative Safeguards Demonstration Programme at Capenhurst," TNA FCO 96/1465/100 (December 8, 1981).
[160] British Nuclear Fuels Limited, "Proposal for a Collaborative Safeguards Demonstration" (1981), 1, attachment to Brown, TNA FCO 96/1465/72 (October 28, 1981).

The Fourth HSP Plenary Meeting, Tokyo, Japan, November 9–13, 1981

The 4th HSP plenary meeting, held in Tokyo, Japan in November 1981, marked the project's turning point. During the HSP's first year, progress had been slow, and at times, HSP efforts provoked dysfunction between its participants, particularly within the Troika. Despite the Boekelo Understanding of March 1981, the issue of undeclared material and equipment continued to be controversial. Owing to displays of good faith by key participants, however, and behind-the-scenes diplomacy by individual delegates, the Tokyo meeting ended up progressing smoothly, setting the HSP in motion towards its ultimate consensus on adopting the LFUA model for verifying the absence of GCEP misuse. While this is not to say that political disputes and gamesmanship entirely disappeared from the HSP after the Tokyo meeting, it can be argued that the seeds of the HSP's ultimate success were sown, via political compromise, in Tokyo.

A key outcome of the Tokyo meeting was a final agreement on how to treat the undeclared issue within the HSP. On the margins of the meeting, Fred Brown held informal meetings with the Dutch and FRG delegations to resolve their dispute over the applicability of undeclared material and activities, and to mend bridges that had been burned in the recent JC (albeit between different actors). Brown subsequently facilitated an informal agreement among all HSP delegations, reinforcing the Boekelo understanding, in his words, to "launder the team reports put to the Plenary to remove direct reference to the clandestine situation."[161] An FRG HSP delegate recalls sitting with the U.S. delegation head, Joerg Menzel, at a Tokyo hotel, editing the U.S. reports line by line,

[161] Fred Brown to Peter Kelly, "The Hexapartite Safeguards Project (HSP): Tokyo Meetings 4-13 November 1981," TNA FCO 96/1465/91 (November 19, 1981), 1.

following this agreement.[162] This new, clearer understanding—to refrain from explicitly addressing misuse scenarios involving undeclared material and equipment—would survive through the rest of the HSP's duration. While this arrangement essentially constituted a concession to the German and Japanese positions, this final solution to the fundamental dispute on the purpose of INFCIRC/153 safeguards provided the common ground necessary for defining the basis for the HSP safeguards approach.

The FRG perspective on the report laundering operation, however, differs significantly from Brown's account. The fact that the FRG delegation cleansed all the team reports is clear, per the FRG BMFT's internal record of the meeting, but the same minutes also state that the FRG had to *concede* its resistance to the possibility of undeclared material and machinery. The relevant language, translated, reads:

> "Under particular pressure from the Troika partners, we had to give up the general reservation regarding rejection of clandestine plants and undeclared material in verification modalities.
>
> To the greatest extent possible, we subsequently cleansed the working group reports, except for a few nebulous formulations that could entail hidden undeclared material."[163]

[162] Interview with FRG safeguards expert (November 2, 2016).

[163] Rüdiger Gerstler, ""Multilaterales Kooperationsprogramm "Kontrollmaßnahmen für GUZ-Anlagen" – Hexapartite Safeguards Project (HSP): 4. Sitzung vom 4.11.81 – 13.11.81 in Tokyo. Zussammenfassender Vermerk über den Sitzungsverlauf," PA AA, B 72 (ZA)/129441 (November 19, 1981), 3.

Original German: "Auf besonderen Druck der Troika-Partner mußten wir den allgemeinen Vorbehalt, bezüglich Ablehnung von heimlichen Anlagen und nichtdeklariertem Material für die Überwachungsmodalitäten aufgeben. Wir haben darauf hin die Arbeitsgruppenberichte mit Ausnahme einiger weniger nebulöser Formulierungen, die noch versteckt undeklariertes Material enthalten könnten, weitestgehend bereinigt.

Thus, the FRG delegation perceived this arrangement as a compromise, under which FRG representatives would concede its right to object to undeclared material and capacity, in exchange for a commitment by the other HSP participants to bury references to the same topics. Considering that the FRG had been raising objections at every occasion at which the slightest possibility of these issues was implied, however, the FRG perception that it had given something up appears to be genuine.

The U.S. delegation also demonstrated willingness to compromise at the Tokyo plenary. At the meeting, U.S. delegates also revealed plans to make a statement in the IAEA Board of Governors, declaring that the United States would accept an inspection system featuring limited cascade access at its own GCEP in Portsmouth, OH,[164] which was under construction at the time. This political initiative by the United States, as has already been argued in the literature,[165] laid the path towards the ultimate success of the HSP, and the decision to adopt limited cascade access for GCEP safeguards. At this point, UK delegation recognized that this action would essentially lock the HSP into the limited access model, which the UK had supported since Euratom inspectors had first attempted to access the Capenhurst cascade halls in the mid-1970s. Fred Brown wrote:

> "When [the U.S.] statement is made it will be difficult for the FRG not to take the same line. The Dutch will accept it and we would have no difficulty to go along with it. The Australians will back the US line as will the IAEA and Euratom. The Japanese will accept the Troika decision. As additional background to the UK view you should be aware that several years ago I obtained a mandate from all interested parties (D/E, FCO, MOD, BNFL) to negotiate a limited access inspection regime with Euratom for application at Capenhurst. For theological reasons to maintain the sanctity of the Euratom Treaty Dr Schleicher the Head of Euratom Safeguards refused to consider anything other than complete access for

[164] Brown to Kelly, TNA FCO 96/1465/91 (November 19, 1981), 1
[165] J. Christian Kessler, "Technical Negotiations in a Political Environment," *The Nonproliferation Review* 20, no. 3 (2013): 493–508.

> his inspectors. It was because of this and the advent of the Agency on the scene that we persuaded the Dutch to discontinue giving access to Euratom inspectors at Almelo. Dr Schleicher very reluctantly accepted a self denying ordinance. If it had not been for the hard Euratom line in the first instance the problem would have been settled years ago and the question of clandestine feeds and clandestine facilities would never have arisen."[166]

With the UK now ready to support limited access, the FRG delegation recognized that its options were limited for continuing its resistance to cascade access. Prior to the plenary, the FRG had viewed UK support to be critical for maintaining its position, recognizing that it would otherwise be alone.[167] By the end of the Tokyo HSP plenary, it was clear that this situation was to transpire.

At this point, however, the United States had not yet formally announced the possibility of limited cascade access at Portsmouth, and so the FRG still had some leeway to advocate for a non-access approach. Furthermore, the creation of the HSP Assessment Group at the Tokyo plenary, which the FRG chaired, provided the FRG with a platform for advancing its non-access platform.

The HSP Assessment Group, November 1981–March 1982

At the Tokyo HSP plenary, the United States, supported by the Netherlands and Australia, proposed creating a new Assessment Group for the HSP, now that the HSP had completed its information collection phase through its four Teams, and was now moving to defining and evaluating possible GCEP safeguards approaches. This initiative was approved by the HSP, and a representative from the FRG BMFT was chosen to chair the committee, as the FRG had not yet

[166] Brown to Kelly, TNA FCO 96/1465/91 (November 19, 1981), 1–2.
[167] Rüdiger Gerstler, "Multilaterales Kooperationsprogramm…," BArch, B 196/110542 (October 29, 1981), 8–9. Original German: "Würde sich nämlich auch UK den Befürwortern eines limitierten Zugangsmodells (US, Aus, NL, IAEO, Euratom (?)) anschließen, würden wir allein die Stellung kaum halten können. UK sollte deswegen um Unterstützung gebeten werden."

led an HSP team (Japan, the UK, Australia, and the USA had chaired teams, and the Netherlands, to the FRG's dismay, had chaired the progress report drafting group for the 4th plenary).[168] The task of the Assessment Group was to evaluate the advantages and disadvantages of GCEP safeguards models based on limited unannounced cascade access and non-access, on the basis of the work that had taken place over the past year, and to recommend a safeguards concept by the March 1982 Sydney plenary. Chairmanship of the Assessment Group clearly gave the FRG an opportunity to persist with its support for non-access.

As the Assessment Group got underway, however, it was clear that the limited unannounced access model carried far more momentum. By mid-December 1981, the U.S. statement on limited cascade access at Portsmouth had been drafted, and was undergoing review at the USDOE, to be released by Christmas.[169] Meanwhile, the FRG BMFT's non-access position was questioned by the FRG Foreign Office (Auswärtiges Amt, AA), which began to take a more active role in the HSP during its second year. The FRG AA noted that the West German enrichment industry actually preferred limited cascade access,[170] which involved the implementation of far less intricate containment and surveillance measures. While the FRG AA recognized potentially negative aspects of cascade access, noting that it would be undesirable for Pakistani inspectors to enter cascade halls, the AA still saw a need to craft a position for the HSP,[171] now that the project was reaching an advanced

[168] Gerstler, "Multilaterales Kooperationsprogramm…," PA AA, B 72 (ZA)/129441 (November 19, 1981), 6.
[169] F. Brown to R.G. Marsh, Letter, SK/20/02, TNA FCO 96/1465/106 (December 17, 1981).
[170] Rouget to BMFT, "Safeguards für GUZ-Anlagen: Hexapartite Project," BArch, B 196/110542 (December 15, 1981), 1–2. Uranit, the German Urenco shareholder, had supported limited cascade access as early as 1979. See: "IAEA-Safeguards für Urenco-Anlagen," Uranit Report TG/570/79/ka/rei (August 21, 1979), attachment to Uranit to W.J. Schmidt-Küster, "Safeguards für Urenco-Anlagen," PA AA, B 72 (ZA)123660/491.23/SB3 (September 6, 1979).
[171] Rouget to BMFT, BArch, B 196/110542 (December 15, 1981), 2.

stage, and that the effort was clearly germane to FRG foreign policy. In doing so, the AA requested consultation from the BMFT.

The BMFT's response, sent in early February 1982, reflected some evolution in its position. Although the BMFT noted the main reasons for its opposition to cascade access to date, most importantly the need to protect commercially sensitive and proliferation-sensitive information, it also noted that the UK was moving further towards the U.S. line.[172] In anticipation of limited access becoming the HSP's favored option, the BMFT prompted the AA to consider conditions for the FRG's approval of limited access—for example, the admission of inspectors only from a given list of nationalities.[173]

As the Assessment Group's work continued, support for the limited access approach grew. In particular, the United States became increasingly emphatic about its preference for limited cascade access. At an FRG-U.S. meeting at the AA on January 22, 1982, U.S. representatives expressed a "certain irritation" to AA officials over the FRG's position on access, pointing out that the UK was now ready make a compromise.[174] By mid-February 1982, following the Assessment Group's first meeting in Jülich at the beginning of the month,[175] it was clear to the BMFT that the United States would only accept a GCEP safeguards approach based on limited access,[176] a position that

[172] Spilker to Auswärtiges Amt Referat 413, "Sicherungsmaßnahmen für GUZ-Anlagen: Hexapartite Safeguards Project (HSP)," PA AA, B 72 (ZA)/129441 (February 1, 1982), 2–3.
[173] Ibid., 3.
[174] Original German: "gewisse Irritation;" Rouget, "Safeguards für GUZ-Anlagen: Hexapartite Project—Deutsch-amerikanische Nuklearkonsultationen im Auswärtigen Amt am 22. Januar 1982," PA AA, B 72 (ZA)/129441 (February 2, 1982).
[175] Gerstler, "Multilaterales Kooperationsprogramm "Kontrollmaßnahmen für GUZ-Anlagen," Hexapartite Safeguards Project (HSP): Empfehlungen von Überwachungskonzepten (Safeguards-konzepte) für Zentrifugenanreicherungsanlagen," PA AA, B 72 (ZA)/129441 (February 16, 1982), 3.
[176] Ibid., 2.

the United States would put in writing by the time of the 5th HSP plenary.[177] At the time, the U.S. supported up to 12 unannounced visits to the Portsmouth cascade areas per year.[178] Meanwhile, the BMFT also began to acknowledge the potential advantages of limited access, which would entail less disturbance to operations and cost for the IAEA and facility operators, easier implementation of safeguards, and that demonstration of measurement techniques and devices could be demonstrated within the HSP's current timeline.[179]

At this point, in mid-February 1982, a momentous change took place in the FRG HSP line: for the first time, the FRG was willing to openly support limited cascade access, motivated both by its increasing isolation within the HSP, as well as its advantages as identified by HSP experts. This new line, however, would depend on three conditions, translated below:[180]

- The issue of clandestine plants and undeclared material would need to be excluded from the HSP;
- All other technology holders, especially the United States, would have to adopt the limited access model; and
- Safeguards activities under the access model would need to be clearly defined and limited, and consistent with Troika and U.S. classification regulations.

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[177] "United States Views on IAEA Inspector Access to Cascade Halls at Uranium Enrichment Plants," PA AA, B 72 (ZA)/129441 (March 29, 1982).

[178] "Forschungs- und Entwicklungsprogramm über Safeguards für Anreicherungsanlagen nach dem Gasultrazentrifugen-Verfahren unter Betiligung von USA, Großbritannien, Niederlande, Bundesrepublik Deutschland, Japan, Australien, IAEA und Euratom (sogennantes Hexapartite Project): Ihr Mittagessen mit Undersecretary of State Kennedy am 1. März 1982," PA AA, B 72 (ZA)/129441 (February 19, 1982), 1.

[179] Gerstler, "Multilaterales Kooperationsprogramm..." PA AA, B 72 (ZA)/129441 (February 16, 1982), 6.

[180] Ibid., 7. Original German: "-Die Problematik heimlicher Anlagen und nicht deklarierten Materials muß ausgeklammert werden…;"
-Auch die anderen Technologieinhaber, insbesondere USA im Hinblick auf Portsmouth, übernehmen das Modell des limitierten Zugangs;
-Es ist anzustreben, daß die im Rahmen des Zugangsmodells zu erwartenden Safeguardsaktivitäten möglichst eindeutig definiert und begrenzt werden… [i]n diesem Zusammenhang muß durch Abstimmung mit der Troika und US noch eine zufriedenstellende Lösung für die GUZ-Geheimhaltungsvorschriften gefunden werden."

The BMFT believed that these compromise conditions would be acceptable for other HSP participants, particularly the United States, which would have a strong interest in carefully defining the conditions of limited cascade access, if they too were to be subject to the same model.[181]

In making its support for limited access conditional, however, the FRG showed that it was not altogether ready to give up on non-access. At an interdepartmental meeting between the AA, BMFT, and the Federal Ministry for Economic Affairs (Bundesministerium für Wirtschaft), the three agencies decided that restrictions on inspector nationalities, both from proliferation-sensitive States (e.g. Pakistan) and commercially sensitive States (e.g. France) would be another condition for the FRG's acceptance of limited access, and that non-access would remain as a backup option if the HSP were unable to agree to the conditions that it desired. The FRG would insist upon fulfillment of these conditions at the 5th HSP plenary in Sydney.[182] The three departments also agreed on a forceful set of talking points supporting the FRG position on undeclared material, in preparation for a high-level meeting in March between BMFT State Secretary Hans-Hilger Haunschild and U.S. Under Secretary of State for Management Richard T. Kennedy, who had recently become involved in HSP affairs. In addition to bringing up the FRG's usual list of concerns, Haunschild would bring up a statement made by U.S. President Ronald Reagan in July 1981, through which the FRG understood that States with good nonproliferation credentials should not be treated with mistrust.[183,184] Furthermore, the FRG would raise the question of how to

[181] Ibid., 8.
[182] "Forschungs- und Entwicklungsprogramm über Safeguards…," PA AA, B 72 (ZA)/129441 (February 19, 1982), 2.
[183] Ibid., 3.
[184] Reagan's statement cited in the FRG record does not explicitly reflect the FRG's understanding of it—the only part of the statement that mentions States with good nonproliferation credentials is "the administration will also not inhibit or set back civil reprocessing and breeder reactor development abroad in nations with advanced nuclear power programs where it does not constitute a proliferation risk." This

consider the possible existence of undeclared plutonium—by the FRG's logic, if undeclared uranium feed could exist at enrichment plants, then by the same token, undeclared plutonium could exist at other points in the fuel cycle.[185] By adopting this strategy, the FRG sought to ensure that its conditions for compromise would be taken seriously and understood at high government levels in other countries, most importantly the United States.

The HSP Assessment Group's report was ready in mid-March 1982, by which point it had already been endorsed by the Tripartite JC.[186] The report's conclusions repeated, almost verbatim, the assessments in FRG policy briefs (quoted earlier in this chapter) of the pros and cons of limited cascade access, as well as the FRG's compromise conditions, with the exception of the requirement that the HSP exclude undeclared material and equipment, which the FRG had already agreed to put to rest at the Tokyo plenary meeting. Most interestingly, the first sentence presented limited access and non-access as equally effective, on a technical basis. This language was crafted deliberately to support the FRG's position, to ensure that any HSP decision in favor of limited access would subsequently be made on a political basis, conditional on the fulfillment of the FRG's conditions, and not on any basis of the relative merits of the two access modes.[187] The conclusions of this report are given below:

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language, nevertheless, implies that states with advanced fuel cycles should be trusted to pursue sensitive nuclear fuel cycle technology, which includes uranium enrichment. See Ronald Reagan, "Statement on United States Nuclear Nonproliferation Policy," Ronald Reagan Presidential Library (July 16, 1981).

[185] "Forschungs- und Entwicklungsprogramm über Safeguards…," PA AA, B 72 (ZA)/129441 (February 19, 1982), 3.

[186] BMFT to AA, "Sicherungsmaßnahmen in Anreicherungsanlagen: Hexapartite Safeguards Project (GUZ-Anlagen)," PA AA, B 72 (ZA)/129441 (March 15, 1982), 2.

[187] Original German: Bei den weiteren HSP-Arbeiten sollten grundsätzlich beide Zugangsmodelle als nv-politisch gleichwertig behandelt werden. Dadurch soll eine Empfehlung zugunsten des Zugangsmodells aus praktischen technischen Gründen nicht ausgeschlossen werden. Wir müssen uns aber, falls die von uns genannten Bedingungen nicht erfüllt werden, den Rückweg zum Nicht-Zugangsmodell offenhalten.

"Conclusions and recommendations

The Assessment Group has concluded that both access and non-access approaches to safeguarding gas ultracentrifuge enrichment facilities are capable of meeting safeguards objectives in respect of countries with INFCIRC/153-type agreements.

The unannounced limited model exhibits three main advantages as compared to the non-access alternative:

1. Less intrusiveness into plant operations and lower equipment and manpower costs, both for the operator and for the inspectorate(s).
2. The implementation of the model, especially in already existing facilities or facilities already under construction, is simpler.
3. The availability, within the timescale of the HSP, of instruments and measurement techniques associated with the access approach may be more credibly demonstrated.

The principal disadvantage of the access model is that it implies a higher risk of proliferation of sensitive technology and the danger of undesirable transfer of commercially valuable know-how.

In light of these considerations, the Assessment Group recommends in principle a safeguards approach within the group of HSP-participants based upon (2) limited (1) unannounced access to cascade areas, subject to the following conditions.

i) Universal acceptance and equal application on the part of all technology holders;
ii) Clear and unambiguous definition and circumscription of the nature and scope [sic.] inspectorate(s)' verification activities;
iii) Satisfactory solution of problems associated with security concerns.

This recommendation is the outcome of a discussion of technology holders participating at HSP.

It is understood that the possible application of a specific safeguards approach to other Technology holders should take into account relevant security/non-proliferation considerations."[188]

BMFT, "Hexapartite Safeguards Project: Politische Rahmenbedingungen für bilaterale US-Konsultationen am 22./23. März 1982 und anschließende HSP-Sitzung in Sydney, 26. März – 2. April 1982," PA AA, B 72 (ZA)/129441 (March 19, 1982), 1.

[188] BMFT to AA, "Sicherungsmaßnahmen in Anreicherungsanlagen: Hexapartite Safeguards Project (GUZ-Anlagen)," PA AA, B 72 (ZA)/129441 (March 15, 1982), 3–5.

Ahead of the 5th HSP plenary in Sydney, largely due to the FRG's negotiating tactics, the decision to adopt limited unannounced access was framed as one borne entirely from political compromise. While the Assessment Group's draft report stated that limited unannounced access and non-access were equally capable, the technical assessment of HSP participants had stated otherwise. The United States had previously reached the conclusion, based on its own technical assessment, that limited cascade access was the only credible approach for verifying the absence of GCEP misuse.[189] According to Joerg Menzel, the UK had reached a similar conclusion through its own study during the HSP Assessment Group's tenure.[190] But while this disparity did provoke some dispute during the Sydney plenary, the political compromise at the heart of the HSP's adoption of the LFUA approach would remain.

The Fifth HSP Plenary Meeting, Sydney, Australia, March 29–April 2, 1982

At the 5th HSP plenary meeting, participants finally agreed to adopt LFUA as the HSP's preferred access mode, subject to the three conditions put forth by the FRG. This compromise, known among HSP participants as the 'Sydney Compromise,' constituted the basis for all further work in the HSP, which subsequently dealt mainly with fulfilling the terms of the deal made in Sydney. This agreement, however, only came after controversy over the wording of the Assessment Group Report's conclusions was settled.

As mentioned in the previous section, the statement in the draft Assessment Group report stated that access and non-access approaches had equal safeguards value, which directly conflicted with

[189] "United States Views…," PA AA, B 72 (ZA)/129441 (March 29, 1982).
[190] Joerg Menzel, Email Communication (August 9, 2017).

U.S. and British analysis. In reaction, the United States first attempted to block passage of the Assessment Group report altogether,[191] before instead suggesting changes to the draft language to which it took exception. The American reformulation of the first sentence of the Assessment Group Report's conclusion is given below:

> "The group's current assessment is that access approaches for application of IAEA safeguards at gas centrifuge uranium enrichments [sic.] facilities are capable of meeting safeguards objectives. In addition, a number of participants consider that non-access approaches are also capable of meeting these objectives."[192]

This change alone, however, was not acceptable to the FRG,[193] as it afforded insufficient flexibility for the FRG to revert to pushing for non-access, in the event that the HSP failed to fulfill the compromise conditions. The FRG countermove was to more directly tie its conditions to LFUA implementation, using language that made the advantages of LFUA acknowledged in the American language conditional only on fulfillment of the three conditions. Thus, the FRG suggested the following reformulation, which would then be placed immediately prior to its list:

> "The group's current assessment is that access approaches for application of IAEA safeguards at gas centrifuge uranium enrichments [sic.] facilities are capable of meeting safeguards objectives, provided that the following conditions which should be studied in detail for each technology are met:"[194]

With this language, in theory, the FRG could then argue, if it were dissatisfied with progress on the compromise conditions, that the HSP did not endorse the adoption of LFUA over a non-access

[191] FRG Embassy Sydney to Bonn AA, Telegram No. 16, PA AA, B 72 (ZA)/129441 (April 1, 1982), 1.
[192] Rouget to Lautenschlager and Gerstler, "Sicherungsmaßnahmen in Urananreicherungsanlagen der Troika: derzeitige Konsultationen über Heksapartite in Sidney, Australien," PA AA, B 72 (ZA)/129441 (March 30, 1982), 2.
[193] Ibid.
[194] Ibid.

safeguards approach. Meanwhile, the U.S. preference only for cascade access would also be reflected. With both sides satisfied, a more "businesslike" and "relaxed" atmosphere returned to the meeting.[195] The conclusion of the Assessment Group report, as approved by the HSP, is given below:

"Conclusions and recommendations

As with all investigations by HSP only centrifuge enrichment plants subject to safeguards under an INFCIRC/153 type agreement for non-nuclear weapon and for nuclear weapon states have been considered.

The group's current assessment is that a safeguards approach based upon limited-frequency unannounced access to cascade areas for application of IAEA safeguards at gas centrifuge uranium enrichment facilities is capable of meeting safeguards objectives. The acceptance of this approach is dependent upon the fulfillment of the following conditions:

(i) Acceptance by all participants and equal application to all technology holders in the HSP.
(ii) Clear and unambiguous definition and description of the nature and scope of inspectorate(s) verification activities.
(iii) Satisfactory solution of problems associated with security concerns with regard to the protection of sensitive information.

In addition, a number of participants consider that non-access approaches are also capable of meeting the safeguards objectives.

The limited-frequency unannounced access model exhibits three main advantages as compared to the non-access alternative:

(1) Less intrusiveness into plant operations and lower equipment and manpower costs, both for the operator and the inspectorate(s).
(2) The implementation of the model, especially in already existing facilities or facilities already under construction, is simpler.

[195] FRG Embassy Sydney to Bonn AA, Telegram No. 16, PA AA, B 72 (ZA)/129441 (April 1, 1982), 1.

(3) The availability, within the timescale of HSP, of instruments and measurement techniques associated with the access approach may be more credibly demonstrated.

The principal disadvantage of the access model is that it implies a higher risk of revealing sensitive information.

The Assessment Group believes that a safeguard approach based upon limited-frequency unannounced access to cascade areas should be studied in detail for each technology to see how the above conditions can be applied."[196]

Now with the Sydney Compromise agreed, the work of the HSP then turned to fulfilling the terms of the agreement. Defining the parameters of LFUA was the first order of business. Each technology holder agreed to "prepare a paper describing their view of the inspection actions and design information which would be useful and acceptable in adopting the limited frequency unannounced access model for their commercial plants."[197] The "broad content" of these papers was to be shared with other technology holders, and then the papers themselves were to be subsequently submitted to the inspectorates by the end of June 1982. Bilateral discussions between technology holders and the relevant inspectorates would then take place, and prior to the next HSP plenary, the inspectorates would prepare a "general paper" discussing possible inspection activities under LFUA, based on the information provided by the technology holders.[198] This paper would then be reviewed at the sixth HSP plenary, which was to take place in Aachen, Germany.

[196] Ibid., 1–2.
[197] FRG Embassy Sydney to Bonn AA, Telegram No. 17, BArch, B 196/110542 (April 2, 1982), 2.
[198] Ibid., 1–2.

The original HSP timeline would have scheduled the next HSP plenary for July 1982, with a seventh meeting in November 1982 at the IAEA in Vienna.[199] Due to the timeline for drafting the LFUA reports, the Aachen plenary was delayed to September 1982.[200] However, due to political discord between the United States and the Troika over their recommended LFUA measures, this timeline would slip further. Even though the HSP focused on hammering technical safeguards measures for the LFUA approach, political dynamics still dominated its discourse.

Defining the Terms of LFUA, Summer–Fall 1982

Given the difficulties that the HSP had to overcome just to agree on LFUA as a general approach, defining the parameters of LFUA was not going to be easy. The Troika partners, for example, still had not reached agreement on how to assess the potential leakage of classified information via limited cascade access. The United States was still taking a very technocentric approach to safeguards design, which was poorly received by the Troika. These issues would ultimately delay the HSP by another two months, pushing back the 6th HSP plenary to November 1982.

In keeping with the HSP's schedule, the first draft of the Troika's LFUA paper was completed on May 7, 1982.[201] The Troika's take on LFUA emphasized the use of visual observation in cascade hall inspections, which made sense for the highly repetitive and visually 'transparent' cascade plumbing design used in Troika facilities at the time, with the use of portable NDA devices only

[199] Gerstler, "Multilaterales Kooperationsprogramm…," PA AA, B 72 (ZA)/129441 (November 19, 1981), 8.
[200] FRG Embassy Sydney to Bonn AA, Telegram No. 17, BArch, B 196/110542 (April 2, 1982), 1.
[201] "Minutes of the Meeting of the Joint Committee held at Bonn on Friday, 2 July 1982," PA AA, B 72 (ZA)/129440 (July 13, 1982), 5.

when necessary, and generally only outside cascade areas,[202] with the exception of enrichment measurements using portable NDA equipment on cascade headers inside cascade halls.[203] In order to address security concerns, the Troika advocated for limiting inspectorates to one inspector each per access, with time limits, predetermined inspection routes during cascade access, concealing cascade areas under construction with physical screens or covering, and restrictions of inspector nationalities to only those of certain States.[204] Average access frequency, "as a political confidence building measure," would be limited to four per year.[205] The JC SOS, now under the chairmanship of Rüdiger Gerstler, reviewed the paper later that month. At that time, Gerstler noted that the security implications of cascade access had not yet been studied by the Troika and encouraged the JC to request that its Security and Classification Working Group (SCWG) review the Troika LFUA paper for potential security issues and present its findings to at the next JC meeting, which the SOS agreed to do.[206]

The SCWG encountered difficulties, however, in assessing the Troika LFUA paper. While the Dutch SCWG representative argued that inspectors would not have access to information classified higher than Restricted, the UK and FRG representatives perceived that information at the Confidential level would be compromised. In particular, the UK and FRG were concerned that the

[202] Rüdiger Gerstler, "Multilaterales Kooperationsprogramm Kontrollmaßnahmen für GUZ-Anlagen "Hexapartite-Safeguards-Projekt-HSP: Sachstandsvermerk für die Mappe von Herrn St zur IAEO-Generalkonferenz, Wien, 20. – 24. Sept. 1982," BArch, B 196/110542 (August 11, 1982), 3.
[203] The final submitted version of Troika LFUA paper was edited to endorse NDA measurements inside cascade areas only at Almelo, if deemed necessary. See "Minutes of the Meeting of the Joint Committee held at Bonn on Friday, 3 September 1982," PA AA, B 72 (ZA)/129440 (September 13, 1982), 11.
[204] Gerstler,"Multilaterales Kooperationsprogramm…," BArch, B 196/110542 (August 11, 1982), 3–4.
[205] Original German: "Durchschnittliche Anzahl von Besuchen 4 x pro Jahr als politische vertrauensbildende Maßnahme." Ibid., 4.
[206] "Minutes of the Meeting of the Joint Committee held at Bonn on Wednesday, 26 May 1982, PA AA, B 72 (ZA)/129440 (June 15, 1982), 11–12.

separative performance of cascades, classified Confidential, could be obtained via repeated inspector access to cascades, in combination with "legitimately available" information.[207] For example, material balance data, which can be used to calculate plant capacity, could be used in conjunction with the known layout of cascade areas to calculate the performance of individual cascades. The performance of individual centrifuges, classified Confidential,[208] could also be calculated from material balance data, in combination with cascade hall dimensions and an estimate of the areal density of centrifuges inside. As uncleared personnel were not to be exposed to information classified higher than Restricted (under the laws of the Troika States), and as Annex II, Paragraph 8(a) of the Treaty of Almelo forbids uncleared visitors from accessing restricted facility areas, or from accessing classified matter without an appropriate access authorization, the UK and FRG argued that an amendment to the Treaty might be needed in order for IAEA inspectors to be admitted to cascade areas.[209] The Dutch representative argued, on the other hand, that the 'Confidential' classification for cascade and centrifuge performance apply only when "details of the cascade layout" and "complete performance data of centrifuge machines" were revealed.[210] Furthermore, Annex II, Paragraph 8 of the Treaty of Almelo, from a Dutch point of view, only applied to nationals of the UK, the Netherlands, and the FRG, as contracting parties, and not to personnel from other States,[211] given that the context of Annex II is to provide a set of rules for the exchange and use of classified centrifuge technology information between the three Treaty parties. Nevertheless, the SCWG reported the majority view to the JC, stating that acceptance of compromising classified information, in violation of the Treaty of Almelo, would

[207] "Comments of the Security and Classification Working Group on the problem of limited access of IAEA inspectors under the aspect of security regulations," PA AA, B 72 (ZA)/129441 (June 29, 1982), 1.
[208] Ibid., 4.
[209] Ibid., 1–2.
[210] Ibid., 2.
[211] Ibid., 3.

have to be a "political decision" taken by the JC. Specific items identified by the SCWG are given in Table 6-4.

Table 6-4: List of classified items that could be compromised during LFUA inspections, as identified by the JC Security and Classification Working Group. Source: "Comments of the Security and Classification Working Group on the problem of limited access of IAEA inspectors under the aspect of security regulations," PA AA, B 72 (ZA)/129441 (June 29, 1982), 4.

Items of Troika Technology which might be revealed by limited access to cascade areas	Possible Breach of Classification Guide	Classification
Type of installation unit (single or block)	B.2.5 Pattern of machines	Confidential
Layout of foundation and the floor mounting of the individual machines	A.3.15 Systems of interconnected containers	Restricted (finished component)
Layout of cascade pipework (welding flanges)	A.3.16 Process gas connections	Restricted (finished component)
Type of inverters	B.3.5 Electrical system	Restricted
Size of cascade or protection unit	B.2.4 Information on cascade	Restricted
Capacity of installation unit, separation factor, flow rate*	A.2.3 Separative output of machines	Confidential
Material of piping and of casing	A.1.2, A.1.3	Restricted
Approximate dimension of centrifuge	A.3.14 Centrifuge housing	Restricted
Cascade piping arrangements	B.2.5 Pattern of machines	Confidential

*Combining design information on plant separative output and plant flow rates.

The JC considered the SCWG's comments on the Troika LFUA paper on July 2, 1982. Per the timeline agreed in Sydney, by this point, the paper should have been shared with the inspectorate, and its outline shared with the other HSP technology holders. The SCWG's findings, however, gave pause to the British and German JC representatives. Peter Kelly, of the UK delegation, suggested that a risk assessment on cascade access be carried out within the following two months.[212] This would also involve delaying submission of the paper for two months, since it would

[212] "Minutes of the Meeting of the Joint Committee held at Bonn on Friday, 2 July 1982," PA AA, B 72 (ZA)/129440 (July 13, 1982), 3.

be difficult to retract anything proposed in the paper after it was made available to the inspectorates. Kelly noted that consultations on classification policy with the United States would also be necessary in order to work on a common approach within the HSP for considering security concerns.[213] While the FRG JC representatives from the BMFT and AA were unsure if delaying the paper would yield much political benefit, they did agree that the HSP needed to establish a standard for the amount of information available to inspectors through LFUA.[214] The Dutch delegation again took the minority opinion, pressing for the timely submission of the paper,[215] but was unable sway the JC, now chaired by the FRG. The JC chairman, Wolf Schmidt-Küster,[216] in summing up the discussion, stated that before "giving the paper away," the Troika should be absolutely clear "on how far one could go, and what would be the limits of inspectorate activities that could be accepted in view of the Troika non proliferation and security obligations."[217] Thus, the JC instructed the SOS to again consider the Troika LFUA paper, and to carry out a risk assessment on possible proliferation risks that its measures might entail by early September 1982, when the next JC meeting would be held, and the FRG would contact the U.S. and Japanese governments to discuss the Troika's desire for common ground on availability of information to inspectors. Meanwhile, Fred Brown, still HSP Chairman, would be informed of the two-month delay that the Troika had imposed.[218]

[213] Ibid.
[214] Ibid., 4.
[215] Ibid.
[216] R.B. Kehoe, *The Enriching Troika: A History of Urenco to the Year 2000* (Marlow, UK: Urenco Limited, 2002), 244.
[217] "Minutes of the Meeting of the Joint Committee held at Bonn on Friday, 2 July 1982," PA AA, B 72 (ZA)/129440 (July 13, 1982), 6.
[218] Ibid.

Security issues, however, were not the only matter that concerned the Troika (rather the FRG and UK) at the time. News of the U.S. LFUA paper's content had reached the HSP participants by July 1982, and some Troika members were unhappy with its recommendations.

At the July 2 JC meeting, the UK revealed that it had gained knowledge of the U.S. LFUA report's conclusion, and reported that it had considerable concerns about its implications for inspector access to proliferation- and commercially sensitive information.[219] Despite Dutch opposition, the JC decided that the UK would attempt to prevent the United States from submitting its LFUA paper to the IAEA.[220] The U.S. draft, however, had already been transmitted on time to the IAEA at the end of June 1982,[221] and could not be recalled. To learn more about the content of the U.S. LFUA proposal, FRG representatives met with the IAEA's Adolf von Baeckmann in Vienna. While von Baeckmann did not pass the paper to the FRG, citing safeguards confidentiality, the FRG learned that the 80-page document called for cascade inspections with two-hour notice period, approximately 50 times per year.[222] This frequency far exceeded the previous U.S. suggestion of 12 cascade visits per year at Portsmouth, as well as the Troika's preference for four visits per year. Measurements during LFUA featured instruments developed by U.S. national laboratories, from NDA on the centrifuges themselves,[223] using instruments such as the dipstick detector, to area monitoring,[224] making use of the U.S.-designed neutron slab detectors. Later that

[219] Auswärtiges Amt Referat 413, "Safeguards bei der URENCO: Hexapartite Project," PA AA, B 72 (ZA)/129441 (July 5, 1982).
[220] Ibid.
[221] Rüdiger Gerstler, "Multilaterales Kooperationsprogramm Kontrollmaßnahmen für GUZ-Anlagen "Hexapartite-Safeguards-Projekt-HSP: Sachstandsvermerk für die Mappe von Herrn St zur IAEO-Generalkonferenz, Wien, 20. – 24. Sept. 1982," BArch, B 196/110542 (August 11, 1982), 3.
[222] FRG Wien Inter to Bonn AA, Telegram No. 408, PA AA, B 72 (ZA)/129441 (July 23, 1982).
[223] Ibid.
[224] Rüdiger Gerstler, "Multilaterales Kooperationsprogramm…," BArch, B 196/110542 (August 11, 1982), 4.

summer, the Troika would learn that the U.S. inspection strategies, in keeping with its prior GCEP safeguards concept development, were entirely based on the use of four different technologies,[225] which could be mixed and matched as appropriate. These technologies were:

- "Individual centrifuge and/or header gamma-ray measurements using a portable, high-purity Germanium (HPGe) detector;"
- "Cascade area gamma-ray measurements using a portable HPGe detector, for example, from the process building bridge-cranes;"
- "Cascade area neutron measurements using a large number of stationary neutron detectors mounted on cascade service modules;"
- "Collimated centrifuge gamma-ray measurements taken with an automated HPGe detector system at the floor level by the operator."[226]

The extensive dependency on NDA within cascade halls was at complete odds with Troika's visual inspection-based philosophy. These differences, which became clear to the UK and the FRG in the summer of 1982, provided all the more urgency for the two States, from their perspectives, to push for a common understanding on the disclosure of sensitive information between the HSP participants, and for successful talks between the FRG and U.S. on this topic, as mandated by the JC.

The FRG planned for high-level talks with the United States on information protection and LFUA measures between Ministerialdirigent Reinhard Loosch, of the BMFT, and Under Secretary of

[225] "Minutes of the Meeting of the Joint Committee held at Bonn on Friday, 3 September 1982," PA AA, B 72 (ZA)/129440 (September 13, 1982), 4.
[226] Hexapartite Safeguards Project, "Inspection Activities Associated with Limited-Frequency unannounced Access Model Applied to Gas Centrifuge Type Enrichments Plants," (February 4, 1983) in R. Buttler et al., "Internationale Safeguards für Zentrifugenanlagen: Konzepte und Verfahren zur Kernmaterialüberwachung und das internationale Hexapartite-Projekt," Jül-Spez-216 (Jülich: Kernforschungsanlage Jülich, August 1983), 20.

State Richard Kennedy. At this point, the FRG AA perceived that the U.S. HSP delegation, under Joerg Menzel, was not sufficiently aware of its concerns about the security implications of cascade access, so escalating the situation to the Under Secretary level was now appropriate.[227] Although the FRG had hoped for a meeting in mid-July, shortly after the decision to delay the Troika LFUA paper,[228] Kennedy was not available for a meeting until early August.[229] In the meantime, the FRG sent talking points, on behalf of the Troika, to its Washington embassy to explain why the Troika had not sent in its LFUA paper draft. The message delivered to Washington strongly implied the possibility of the Troika putting its support, once again, behind the non-access model, while remaining committed to the framework of the Sydney Compromise, reading, "Troika decision not to submit limited access paper to IAEA and Euratom is no reversal of agreement to consider both access and non-access model."[230] Nevertheless, the talking points were clear about the Troika's (principally, the FRG's) main concern, which was that

> "limited access pre-requires an understanding among allies that it would not jeopardize non-proliferation through dissemination of sensitive information to uncontrollable IAEA staff (both inspectors and headquarters staff including computer-aided safeguards information treatment division… and accessible to proliferation risks in third world)."[231]

[227] Original German: "Es wurde daher vereinbart, Under-secretary Kennedy auf dieses Problem aufmerksam zu machen, weil auf der amerikanischen Arbeitsebene, insbes. bei Menzel (ACDA), nicht das nach Auffassung der Troika notwendige Verständnis für die NV-politische Problematik der bisher von den USA vertretenen Ansichten angetroffen wird." Rouget, "Safeguards für Urananreicherungsanlagen nach dem Gasultrazentrifugenverfahren: sog. Heksapartite Project (HSP)," PA AA, B 72 (ZA)/129441 (July 23, 1982).
[228] Dahlhoff, "Hexapartite Safeguards Project: Ferngespräch Botschaft (Dr. Frenzel)'BMFT (von Hees) am 07.07.1982," BArch, B 196/110542 (July 8, 1982).
[229] FRG Embassy Washington to Bonn AA, Telegram No. 3378, PA AA, B 72 (ZA)/129441 (July 31, 1982).
[230] FRG BMFT to Bonn AA, Telegram No. 3144, PA AA, B 72 (ZA)/129441 (July 21, 1982).
[231] Ibid.

The FRG-Kennedy meeting was finally held on August 4, 1982. The FRG's record indicates that the meeting was brief, and that Kennedy was not particularly surprised by the Troika's actions or rationale, and did not advocate particularly forcefully for the U.S. LFUA position.[232] Instead, Kennedy supported further U.S. consultations, once the Troika study on LFUA-related security issues had been completed.[233] Bilateral U.S.-FRG talks were planned for late August 1982, as well as after the next JC meeting, which would review the security study, scheduled for September 3.[234]

Kennedy's stance essentially put the Troika in the driver's seat to define the terms of LFUA. Not only did the Troika already have additional negotiating power through the fact that it contained the only State with an operating commercial facility, but now the United States had also demonstrated that it was not particularly willing to push hard for implementation of its technology, or its conceived GCEP safeguards approach. The United States, during talks led by Kennedy and Loosch on August 25, 1982, did not even express concern about the HSP schedule delay, as long as the project would conclude by the February 1983 IAEA Board of Governors meeting.[235] By this stage of the HSP, it seems that the United States was far more concerned about the HSP successfully coming to consensus on a GCEP safeguards approach, rather than advocating for its own ideal approach, as it had done in years past. Meanwhile, the FRG and United States now shared similar views on ways of addressing security issues: for example, both parties agreed at the

[232] FRG Embassy Washington to Bonn AA, Telegram No. 3413, PA AA, B 72 (ZA)/129441 (August 4, 1982).
[233] Ibid.
[234] FRG Embassy Washington to Bonn AA, Telegram No. 3511, PA AA, B 72 (ZA)/129441 (August 10, 1982).
[235] FRG Embassy Washington to Bonn AA, Telegram No. 3702, PA AA, B 72 (ZA)/129441 (August 25, 1982).

meeting that the IAEA and technology holders could negotiate informal arrangements so that the IAEA would only designate certain nationalities to inspect GCEPs.[236]

Given the U.S. position, the FRG had room to advocate for an extremely minimalistic, non-technical attitude towards LFUA activities. In a BMFT position brief drafted on August 11, 1982, a week after the first Kennedy meeting, Rüdiger Gerstler wrote that cascade access was to be viewed as nothing more than a confidence building measure, without any connection to safeguards objectives. To the FRG, the primary goal of NPT safeguards was still the verification of declared nuclear material, which could be accomplished at GCEPs with a non-access model.[237]

Thus, going into the September 3 JC meeting, the Troika (under the FRG's leadership) enjoyed a favorable position for negotiating its preferred LFUA approach—which meant minimizing the use of NDA equipment within cascade areas. This is essentially what happened. The SOS security and classification review of the Troika LFUA approach did not raise any unacceptable risks for any of the Troika members. The JC, however, upon initiative of the FRG, made the proposed LFUA approach even more restrictive than they had originally proposed in their original draft. The disparity between the U.S. and Troika concepts for NDA use was still an unresolved issue at the

[236] "Minutes of the Meeting of the Joint Committee held at Bonn on Friday, 3 September 1982," PA AA, B 72 (ZA)/129440 (September 13, 1982), 4.

[237] Original German: "Wir sehen dagegen für Staaten, die den NV-Vertrag unterzeichnet haben, die primäre Safeguardsaufgabe in der Kontrolle von erklärtem Kernmaterial. Diese Safeguardsaufgabe kann im Prinzip auch durch Nichtzugangsmodelle erzielt werden. Als vertrauensbildende Maßnahme (ohne Bezug zu den vorläufig quantifizierten Überwachungszielen) und aus Gründen einfacherer Kontrollverfahren waren wir gewillt, unter den oben aufgeführten Bedingungen einen limiterten Zugang in Betracht zu ziehen, um Design-Verifikationen durchführen zu können." Rüdiger Gerstler, "Multilaterales Kooperationsprogramm Kontrollmaßnahmen für GUZ-Anlagen "Hexapartite-Safeguards-Projekt-HSP: Sachstandsvermerk für die Mappe von Herrn St zur IAEO-Generalkonferenz, Wien, 20. – 24. Sept. 1982," BArch, B 196/110542 (August 11, 1982), 5.

time—while the U.S. paper, which had proposed four different implementation modes for NDA equipment, the Troika was still intent on keeping NDA outside cascade areas.[238] Given that the U.S. LFUA proposal was so heavily dependent on NDA within cascade halls, however, Troika representatives realized that they would probably have to concede to some degree of this approach. Reinhard Loosch, also a member of the FRG JC delegation, entreated the Troika to "keep a sufficient margin for negotiations rather than of [sic.] offer already now the most far reaching access model going to the limits of the Troika's acceptance."[239] Gerstler suggested amending the Troika LFUA paper to allow for NDA "only on the process gas pipe work outside the cascade hall, after veryfying [sic.] that this pipework connects directly with the selected cascade."[240] By doing so, the Troika could then offer NDA only on cascade headers *inside* cascade halls as a concession, at a later stage, if necessary. Nevertheless, the Dutch government, still championing a more liberal approach to cascade access, was concerned about the Troika appearing to refute the use of NDA inside cascade areas altogether. As a result, the following language on NDA was agreed for the amended Troika LFUA paper, which was finally submitted to the inspectorates during the week of September 6, 1982:

> "In addition and, if necessary, enrichment measurements by portable NDA equipment may be made on the cascade connection to headers. Such measurements would be made outside the cascade hall, but it is accepted that in the case of the existing Almelo plant further study of the optimum method of taking measurements may need to be explored including the taking of measurements inside the cascade hall."[241]

[238] "Minutes of the Meeting of the Joint Committee held at Bonn on Friday, 3 September 1982" PA AA, B 72 (ZA)/129440 (September 13, 1982), 8–9.
[239] Ibid., 7.
[240] Ibid., 8.
[241] Ibid., 11.

In turn, the Troika also agreed to stress to the IAEA that its LFUA proposal, as submitted, represented the utmost limit, in terms of safeguards measures acceptable to the three governments. In a subsequent JC meeting, Peter Kelly stated that the Troika had agreed "to offer not one millimeter more than the Troika proposal on access to cascade halls."[242] By adopting a such a firm position, in the face of a more pliant U.S. negotiating team,[243] the Troika was well positioned to negotiate NDA measures under the HSP on its own terms, which is reflected in the HSP's agreed LFUA approach, which only permits NDA within cascade areas for performing enrichment measurements on cascade headers inside cascade halls.

To reinforce the Troika's rationale for its proposed NDA strategy, the JC agreed to offer the Capenhurst E21 demonstration plant as a venue for an HSP 'integral exercise,' which had been proposed earlier by the IAEA. At Capenhurst, the necessity of cascade header enrichment measurements could be demonstrated outside the cascade halls, lending technical credibility to the Troika position.[244] The cascade headers within the E21 cascade hall, according to a former IAEA staff member, were positioned too high and out of reach to make NDA measurements practical. Instead, the process piping would need to be traced through the cascade area wall, and measurements would have to be taken outside the cascade boundary.[245]

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[242] "Minutes of the Meeting of the Joint Committee held at Bonn on Thursday, 28 October 1982," PA AA, B 72 (ZA)/129440 (November 26, 1982), 6. See also "Minutes of the Meeting of the Joint Committee held at Bonn on Friday, 3 September 1982" PA AA, B 72 (ZA)/129440 (September 13, 1982), 5.

[243] An FRG position brief from September 30, 1982 notes that the United States had recently adopted the position that the HSP should refrain from trying to produce detailed descriptions of verification approaches, but instead formulate general principles for GCEP safeguards. From this, the FRG inferred that the United States feared further delays (or failure) of the HSP, or perhaps that U.S. interest in the HSP had fallen since the start of the project. See Auswärtiges Amt, "Sitzung des Joint Committee vom 3. September 1982: Hexapartite Project," PA AA, B 72 (ZA)/129440 (September 30, 1982).

[244] "Minutes of the Meeting of the Joint Committee held at Bonn on Friday, 3 September 1982" PA AA, B 72 (ZA)/129440 (September 13, 1982), 8–10.

[245] Interview with a U.S. safeguards expert (August 16, 2017).

The Troika LFUA proposal was not the only paper that was delayed. The Japanese delegation, in fact, chose to hold back its LFUA paper beyond even the 6th HSP plenary in Aachen. At previous HSP milestones—for example, during the decision to endorse LFUA during the run-up to the 5th HSP plenary in Sydney—Japan had followed the Troika's lead, essentially only giving its consent once the rest of the HSP participants had reached agreement on the issue at hand. In this case, Japan's strategy was no different. During the September 3 JC meeting, Fred Brown, as a UK JC delegate, saw a need to pass on the approved Troika LFUA paper to Japan as quickly as possible, not only to demonstrate to the Japanese that the Troika was seriously committed to developing an LFUA concept, but also to influence the Japanese line to be as similar as possible as that of the Troika.[246] Transmission of the paper, however, was not sufficient for moving Japan forward. By October 1982, the Troika put plans in place for a demarche in Tokyo, initiated by the FRG, to push Japan to produce an LFUA concept that it could endorse. But while the Troika had believed that its LFUA paper submission was sufficient to get Japan to do the same, the Japanese government also believed that the Troika needed to confirm that the Sydney Compromise conditions had been satisfied, before supporting a particular LFUA approach. By contrast, the position of the Troika was that its recommended LFUA approach would be acceptable, on the assumption that the Sydney conditions would be met at some point in the future.[247] In mid-October 1982, Japan released a paper elaborating specific measures to be met in order for the Sydney Compromise to be satisfied. Regarding the universality criterion, Japan insisted upon the USA and UK putting their centrifuge

[246] "Minutes of the Meeting of the Joint Committee held at Bonn on Friday, 3 September 1982" PA AA, B 72 (ZA)/129440 (September 13, 1982), 9.
[247] "Contents of a German Embassy's demarche in Tokyo on behalf of Troika governments," Annex to BMFT to AA, "GUZ-Zusammenarbeit: Hexapartite Safeguards Project," PA AA, B 72 (ZA)/129441 (October 13, 1982).

enrichment plants at Portsmouth and Capenhurst on their respective voluntary offer lists, but also that the IAEA then select the facilities for safeguards application in perpetuity. Japan also expected written commitments from the two countries and the IAEA to do so.[248] On the matter of equal application, Japan proposed that GCEP safeguards should be applied in each HSP State on the basis of their LFUA paper submissions, instead of a generic HSP-wide approach,[249] making for an interesting interpretation of the meaning of equal application! For definition of safeguards measures, Japan expected the IAEA to draft a "general paper" describing the "nature and scope" of verification activities, including limitations for inspector activities inside cascade areas, including visit frequency, maximum inspection times, defined inspection routes, permissible locations for access, and escort policies. NDA, optical and acoustic measurements were not to be permitted in cascade areas.[250] For addressing security concerns, Japan called for permitting the physical concealment of non-safeguards relevant equipment that could reveal sensitive information, an agreed procedure between the IAEA and technology holders for designating IAEA GCEP inspectors, and for ensuring that design information, FAs, and FA negotiation records be treated as safeguards confidential.[251]

But despite being highly specific about how to satisfy the Sydney conditions, in keeping with prior form, Japan was more interested in seeing the Troika declare its satisfaction with their fulfillment, prior it choosing to do the same. During the FRG's demarche to the Science and Technology Agency of Japan and the Japanese Ministry of Foreign Affairs, Japanese representatives stated that

[248] Science and Technology Agency of Japan, "Procedures for Discussion on the Conditions to Adopt Limited Frequency Unannounced Access Approach" (October 1982), Annex to FRG Embassy Tokyo to Bonn AA, Telegram No. 978, PA AA, B 72 (ZA)/129441 (October 20, 1982).
[249] Ibid.
[250] Ibid.
[251] Ibid.

their LFUA paper could be presented in Aachen, if the Troika were to speak positively about progress regarding the Sydney Compromise.[252] The Japanese also reported that the United States was willing to work towards meeting its demands,[253] which the U.S. would soon confirm through written comments on the Japanese elaboration on the Sydney conditions.[254]

Between the fifth and sixth HSP plenary meetings, political bargaining dominated discourse between HSP participants over LFUA activities. Although the Troika seriously considered the security implications of inspector access to cascade areas during the summer of 1982, a significant portion of its motivation to do so came from its desire to avoid losing bargaining power by having to withdraw support for measures that it would have otherwise previously endorsed. The question of whether to use NDA in cascade halls was considered by the Troika less in terms of how different types of NDA could contribute to safeguards effectiveness or efficiency, but instead in terms of which NDA measures could be offered or conceded in order to result in the Troika's preferred outcome. Meanwhile, Japan remained fixated on fulfillment of the Sydney Compromise, ahead of any technical discussion on specific LFUA measures at all. Nevertheless, conditions immediately prior to the Aachen plenary were ripe for constructive dialogue. With the HSP now about to exceed its originally planned 2-year timespan and the new February 1983 BoG deadline only three months away, the pressure was on for its participants to reach agreement. The United States, by this point, was open to addressing Troika and Japanese concerns about LFUA, and seemingly less interested in championing its own GCEP safeguards concepts. As the sixth HSP plenary drew near, prospects for confrontation between participants were lower than during previous sessions.

[252] FRG Embassy Tokyo to Bonn AA, Telegram No. 995, PA AA, B 72 (ZA)/129441 (October 26, 1982).
[253] Ibid.
[254] "Hexapartite Safeguards Project (HSP): U.S. Comments on Japanese Discussion Paper," PA AA, B 72 (ZA)/129441 (October 27, 1982).

The Sixth HSP Plenary Meeting, Aachen, West Germany, November 1-5, 1982

The main purpose of the 6th HSP plenary meeting was to discuss the paper on LFUA that the inspectorates had prepared, using the U.S. and Troika LFUA concepts as a basis. This paper, in combination with a second inspectorate-drafted paper drafted later that detailed safeguards activities outside cascade halls, would eventually form the basis of the HSP safeguards approach agreed at the end of the project. This final report would satisfy, in large part, the second Sydney condition on definition of safeguards measures. In November 1982, however, the inspectorates' LFUA paper was still an early draft, as less than two months had passed by since the Troika had provided its own LFUA concept. Significant questions, along with the disparities between the Troika and U.S. positions, were unresolved. The inspectorates were unsure how to handle the differences in NDA use proposed by the two sides, for example. Perhaps most critically, the frequency of cascade hall inspections had not yet been examined by the HSP and was not yet specified in the paper. No agreement was made at the 6th HSP meeting however, on cascade access frequency.

Technical details on inspection activities inside cascade areas were to be worked out at a separate meeting, planned to be held in London on December 13–16, 1982. While all HSP parties would be present, however, this subsequent session would not be considered as an official HSP plenary meeting, and was instead conceived as a drafting group. At this meeting, participants would rework the inspectorates' paper submitted to the 6th HSP plenary into a form that could be used in the final HSP document, sorting out the technology holders' policy differences over matters including

inspection frequency and NDA use once and for all. Prior to the London drafting meeting, and after the 6th HSP plenary, the integral exercise offered by the Troika was to take place at Capenhurst, during which the Troika would demonstrate header pipe enrichment measurements outside cascade areas, along with other technical safeguards measures.

At the 6th HSP plenary, discussions were held over how exactly to satisfy the three Sydney conditions. HSP participants, likely to encourage Japan to finally embrace the LFUA concept, ended up endorsing the Japanese measures for fulfilling the Sydney compromise. At the Aachen plenary, the HSP agreed to the following, which constituted an almost verbatim copy of the Japan's written proposal:

"1. Prerequisite for universal acceptance
The United States and the United Kingdom will take action to put the commercial centrifuge enrichment facilities at Portsmouth and Capenhurst onto their eligible lists in voluntary safeguards submission agreement and subsequently the IAEA intends to choose those facilities on the eligible lists as safeguards application facilities.

2. Establishment of facility attachment
(1) In applying LFUA as the safeguards approach to be applied at each specific facility in the course of negotiation of facility attachment between the state of respective technology holder and the IAEA, the view of respective technology holder and the inspectorates on LFUA described in their papers submitted to the HSP would be fully taken into consideration.
(2) Inspector's routine activities in the cascade area including frequency, maximum time, normal route and possible access place and escort arrangements should be clearly defined in the facility attachment for respective facility. This will be considered in conjunction with the inspection activities outside the cascade halls.
(3) Necessary measures for protection of sensitive information may be clearly defined in the facility attachment for respective facility.

3. Administrative arrangements
(1) The IAEA and the Government of each technology holder should cooperate in identifying the unique technical requirements for IAEA inspectors who make inspection at each specific enrichment facility.

(2) Design information, facility attachment and records of negotiation on them should be treated as safeguards confidential by the IAEA."[255]

In addition to discussion over the Japan's proposed measures, HSP participants also engaged on the issue of inspector nationalities on the margins of the plenary meeting. Following INFCIRC/153, it is the prerogative of the IAEA to designate inspectors for each State under comprehensive safeguards, after which the State has the option to object to designees.[256] While INFCIRC/153 is explicit about the IAEA having the sole right to choose inspectors, however, no definite language exists over the assignment of inspectors to visit facilities in a State, once he or she has been designated for that State. Furthermore, INFCIRC/153 does not preclude the IAEA's designation of inspectors of certain nationalities via prior informal agreement with a State. In Aachen, Adolf von Baeckmann reported to the technology holders that the IAEA Office of Legal Affairs and the IAEA Director General recognized the possibility of selecting only inspectors that met a set of certain agreed criteria, including restrictions on inspector nationalities, for carrying out GCEP safeguards inspections, and that inspectors designated for a given State could be excluded (on the IAEA's prerogative) from accessing GCEPs within the same country.[257]

Selecting the 'ideal' GCEP safeguards inspector, from the technology holders' perspective, involved a delicate balancing act. On one hand, as previously mentioned, inspectors from proliferation sensitive non-NPT States (e.g. Pakistan, or South Africa) were undesirable, as were

[255] "Aachen, 2.11.1982," Memorandum, PA AA, B 72 (ZA)/129441 (November 2, 1982), 1–2.
[256] "The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons," INFCIRC/153 (corrected) (Vienna: International Atomic Energy Agency, June 1972), para. 9, 85.
[257] FRG Auswärtiges Amt to BMFT, "IAEO, Sicherheitsmaßnahmen für GUZ-Urananreicherungsanlagen; 6. Tagung des Hexapartite Safeguards Project (HSP) in Aachen ab 1. November 1982," PA AA, B 72 (ZA)/129441 (November 5, 1982), 2–3.

inspectors from countries that were developing competing enrichment technologies, such as France (from the Troika's perspective). Inspectors from France and Italy, in fact, had been barred from accessing cascade areas at Almelo during Euratom inspections.[258] At the same time, however, technology holders also had an interest in having only experienced, highly capable inspectors visit GCEPs, who were better versed in information protection practices and less likely to raise false alarms. These inspectors often came, however, from States with developed nuclear fuel cycle capabilities, which in many cases were also commercial competitors with the host State. One possible solution, raised by Japan, would be to restrict inspectors to those from Western nuclear weapon states that were also technology holders (i.e. the United States and the UK).[259] Von Baeckmann raised the possibility of also restricting the pool to countries with 3 or more years of experience with GCEP technology,[260] presumably under the assumption that States with a mature centrifuge enrichment capability would have little incentive to misappropriate design information from another technology holder. The question of GCEP inspector selection, nevertheless, would continue to be examined in the closing months of the HSP, and persisted as an unresolved issue after the HSP formally ended in February 1983.

Following the Aachen meeting, discussion continued over how exactly to satisfy the Sydney conditions—while the Japanese measures had been agreed by all HSP participants, in some cases, they did not denote specific actions that could be recorded as complete, and subsequently used as concrete milestones towards fulfillment of the Sydney Compromise. The United States sought to

[258] Rouget to BMFT, "Safeguards für GUZ-Anlagen: Hexapartite Project," BArch, B 196/110542 (December 15, 1981), 2.
[259] FRG Auswärtiges Amt to BMFT, "IAEO, Sicherheitsmaßnahmen…" PA AA, B 72 (ZA)/129441 (November 5, 1982) (November 5, 1982), 2.
[260] Ibid.,

address this issue in December 1982, further elaborating on the accepted Japanese proposal. For the universality and equal application condition, the United States proposed a formal exchange of intergovernmental notes, codifying each HSP technology holders' acceptance of LFUA. The two HSP Nuclear Weapon States, in addition, would restate their commitments to offering the Portsmouth and Capenhurst GCEPs for IAEA safeguards in these notes, while the IAEA would provide a "letter of intent" as a commitment to selecting the two facilities from the U.S. and UK VOA lists.[261] Nevertheless, the U.S. proposal recognized that Congress, which would need to be informed of the addition of the Portsmouth GCEP to the U.S. VOA, could reject this action, while assuring that such a situation would be unlikely[262] (fear of congressional sabotage would still become a concern among other HSP technology holders in the coming months). Regarding the second condition (definition of safeguards measures), the United States explicitly suggested that the combined HSP paper, containing both activities to be conducted inside cascade areas (to be drafted in London) and outside cascade areas, would be sufficient. Finally, the United States proposed that the security condition be "met unilaterally by each technology holder at the successful conclusion of the HSP through the acceptance of LFUA as contained in the report needed to fulfill the second condition and the commitments made in satisfying the first condition.[263]

While the U.S. suggestions to address the first and second conditions would prevail, addressing security via the unilateral actions of technology holders was not sufficient for other HSP participants, who attached great significance to the inspector nationality issue, and to the IAEA's ability to handle sensitive information in a secure manner. As will be discussed, HSP participants

[261] "Summary of U.S. Views on HSP Matters," PA AA, B 72 (ZA)/129441 (December 8, 1982), 2.
[262] Ibid., 3.
[263] Ibid., 3.

would eventually resolve these issues, but not until after the formal end of the HSP. This was, in part, because of the more immediate business of agreeing on the details of the HSP safeguards approach, which would be put forth to the final HSP plenary in Luxembourg, to be held on January 31–February 4, 1983.

Drafting Meeting on Inspection Activities Inside Cascade Halls, December 13–16, 1982

In mid-December 1982, more than 2 years after the HSP began, agreement was finally reached on specific safeguards measures to be used by inspectors inside cascade halls. Disputes over inspection frequency and NDA implementation, which had eluded resolution at the Aachen plenary despite the good intentions of HSP participants, were finally put to rest. However, resolution of key differences between the U.S. and Troika LFUA concepts,[264] including provisions for NDA and cascade access frequency, were nevertheless resolved via political compromise.

The drafting meeting began exactly one week after the Capenhurst integral experiment, whose purpose had been to provide a test bed for some of the measurement techniques and activities that were to be considered by the London Group. Nonetheless, although the inspectorates "unanimously confirmed" that the experiment had been "a complete success," apparently very little experience from the exercise was actually used during the redrafting of the inspectorates'

[264] Japan finally tabled its LFUA concept at the London meeting in December 1982, but its content was not deliberated in detail, as it was too late to incorporate Japan's suggestions into the inspectorates' draft LFUA paper. Gerstler, "Multilaterales Kooperationsprogramm Kontrollmaßnahmen für GUZ-Anlagen "Hexapartite-Safeguards-Project: Zusammenfassender Bericht der HSP-Sitzung vom 13.–16.12. in London," PA AA, B 72 (ZA)/129441 (December 23, 1982), 2.

LFUA paper.[265] Instead, the meeting focused on bargaining over the inspection activities to be used under LFUA inspections, and on measures for upholding the Sydney Compromise.

On the frequency question, the London Group agreed on 4-12 LFUAs per year, for locations up to 1,000 tSWU/yr, which roughly equated to the capacity of the largest facilities under construction (or planned) at the time. Minutes from the FRG give five technical factors that were considered in selecting this frequency range, which were:

- Facility capacity that could be employed in a misuse scenario
- The time and technical difficulty of reconfiguring a plant for HEU production
- HEU production time
- Time required to restore the plant to its original condition, following HEU production
- Frequency and duration of inspections outside cascade halls

Additionally, the FRG reported that the risk of sensitive technology transfers to inspectors was also considered, albeit tacitly.[266]

The 4–12 LFUA/year frequency was consistent with these factors, although the exact methodology linking the factors and LFUA frequency is unclear. Under some assumptions, however, 4–12 LFUA/year may provide fairly high confidence in the absence of misuse. If a given plant were

[265] Ibid., 1. Original German: "Von den Teilnehmern an diesem Experiment, insbesondere von den Inspektoraten, wurde einhellig bestätigt, daß dieses Experimente, Steigerung des Verständnisses der safeguardsrelevanten Auslegungsparameter, ein voller Erfolg gewesen sei. Die Auswirkungen auf die konkrete Diskussion des Modellansatzes waren aber minimal."

[266] Ibid., 3–4. Original German: "Beeinflußt wird diese Frequenz von:

- der für einen eventuellen Anlagenmißbrauch angesetzten Anlagenkapazität
- der Zeit und dem technischen Schwierigkeitsgrad einer eventuellen Umstellung zur "HEU"-Produktion
- der "HEU"-Produktionsdauer
- der Zeit zur Wiederherstellung des ursprünglichen Zustandes
- Frequenz und Dauer der Inspektionen außerhalb der Kaskadenhalle

Und, nicht offen ausgesprochen, vom Risiko eines sensitiven Technologietransfers durch den Inspektor."

assumed to be impossible to reconfigure while keeping centrifuges running, then a misuse 'episode' might take on the order of months, including the time required for restoring the facility to its original state. If such a scenario were to take 60 days to execute, for example, the detection probability of a single episode within a calendar year using quarterly LFUA visits (ignoring the fact that misuse might be detectable during monthly interim inventory verification inspections via inconsistencies in mass balance, and assuming a 100% detection probability during LFUA) would be about 51%, which would constitute a substantial risk to the operator.[267] If the duration of a misuse episode were only one month, this probability would be approximately 29%. It is plausible that these detection probabilities might have been deemed large enough to effect a sufficiently strong deterrent at facilities that would require on the order of months to misuse significantly, and thus, would have been supported by technical evaluation.

Another logic behind the agreed LFUA frequency, is that it merely reflected a compromise between the Troika (and by proxy, Japanese) and U.S. LFUA models. The Troika proposal had consistently supported quarterly LFUA visits, which had appeared in Troika HSP documents extending back to its Team 4 paper from the summer of 1981 and had been conceived not as a technical measure for timely detection of misuse, but as a measure for building political confidence in the absence of misuse. Meanwhile, the upper limit of 12 cascade visits per year represented the lower bound of the LFUA frequencies proposed by the United States, as well as the upper bound on cascade visits that it had proposed for the Portsmouth GCEP earlier in 1982. FRG meeting

[267] The fraction of time, during a single year, in which misuse is taking place is 60/365=0.1644. The probability of at least one inspection taking place during misuse of the plant is $1-(1-0.1644)^4 = 0.512$.

minutes even called the 4–12 LFUA/year range, for contemporary 1000 tSWU/a facilities, a "chosen compromise formulation."[268]

The London Group addressed NDA within cascade halls in a similar manner. The Netherlands, as ever, underlined its desire for inspectors to perform NDA measurements inside cascade halls as a "crucial confidence building element," and so the Troika conceded this right to the inspectorates.[269] Thus, in essence, the Troika LFUA proposal, with quarterly cascade visits and NDA limited to header pipe monitoring, was fully implemented in the HSP LFUA approach. Nevertheless, the key elements of the U.S. LFUA—and NDA—design were also preserved in the final HSP concept. The London Group averted a dispute over cascade hall NDA measures by prescribing different LFUA inspection activities for Urenco/Japanese plants and U.S.-type facilities. While valve and piping arrangements could be determined by visual inspection for the former plant type, allowing NDA to be used as a supplementary measure, the Group recognized that visual observation would be far less effective in U.S.-designed GCEP, where routine preventative maintenance took place, and materials and equipment were constantly moving in and out of the cascade area. The HSP LFUA approach, therefore, still called for use of the four U.S. NDA technologies in plants "with lesser "transparency" characteristics,"[270] while the more "transparent" plants would only be subject to cascade header monitoring, using portable NDA equipment.

By the time of the London meeting, even though cascade header enrichment monitoring had been the Troika's only favored NDA option, development work on a fieldable device had yet to take

[268] Ibid., 3. Original German: "Gewählte Kompromißformel."
[269] Original German: "entscheidendes vertrauensbildendes Element," Ibid., 4.
[270] Hexapartite Safeguards Project, "Inspection Activities…," (February 4, 1983), in R. Buttler et al., "Internationale Safeguards für Zentrifugenanlagen…," 19–20.

place in earnest. Although the U.S. LFUA concept mentioned header pipe monitoring using an HPGe detector, this application had not been the subject of detailed study, unlike development of the dipstick detector or the ROBIN. Designing an external header enrichment monitor, in fact, was a considerable challenge. By the early 1980s, Los Alamos National Laboratory (LANL) had developed an in-line unit header monitor for measuring the enrichment of UF_6, which performed passive measurements of the 186 keV photon emission from ^{235}U using a thallium-doped sodium iodide detector, along with transmission measurements to calculate UF_6 density using the 60 keV gamma line from ^{241}Am.[271] Taken together, these two parameters could be used to calculate the enrichment of the UF_6 contained within a unit header pipe. The system was designed to be installed on dedicated bypass piping,[272] parallel to headers, which would presumably of allow for the equipment to be periodically taken offline and cleaned of solid uranyl fluoride deposits resulting from the exposure of the equipment to UF_6. ^{235}U contained within these deposits can interfere with the 186 keV gamma measurement, which under ideal (and unrealistic) circumstances, would only be sensitive to material in the gas phase flowing in the pipe. Safeguards inspectorates did not have the luxury of modifying plant piping, as the in-line monitor would require. As such, a fully external on-line enrichment monitor would need to account for deposits by somehow discriminating between 186 keV photons emitted from pipe deposits, and the same photons emitted from gas inside a pipe, only considering the effects of the latter. Furthermore, the 60 keV gamma

[271] J.W. Tape et al., "Selected Nondestructive Assay Instrumentation for an International Safeguards System at Uranium Enrichment Plants," Proceedings of the 20th Meeting of the Institute of Nuclear Materials Management (Albuquerque, 1979); Richard B. Strittmatter, "A Gas-Phase UF_6 Enrichment Monitor," *Nuclear Technology* 59, no. 2 (1982): 355–362.
[272] R. B. Strittmatter, J. N. Leavitt, and R. W. Slice, "Conceptual Design for the Field Test and Evaluation of the Gas-Phase UF_6 Enrichment Meter," LA-8657-MS, Los Alamos Scientific Laboratory, 1980. https://www.osti.gov/scitech/servlets/purl/6702244.

transmission measurement technique used in the in-line monitor was insufficiently sensitive for use in cascade headers, which operate at significantly lower pressure than unit headers.

A fieldable, portable external cascade header enrichment monitor was not ready for safeguards use until approximately two years after the HSP ended. By 1985, Los Alamos National Laboratory had developed a device known as the CHEM (an abbreviation of 'cascade header enrichment monitor'),[273] which was subsequently used for the cascade header measurements specified in the HSP. The CHEM system made use of an HPGe detector, and like the in-line monitor that came before it, measured the signal from the 186 keV gamma line from ^{235}U. The CHEM detector was placed inside a collimator specifically designed, based on pipe geometry,[274] to eliminate exposure of the detector to photons originating from wall deposits. To quantify the amount of UF_6 in the pipe, the CHEM relied on measurement of X-ray fluorescence emissions from uranium (also in the HPGe detector), propagated by a collimated ^{57}Co source. The positioning and collimation of both the source and detector were designed to eliminate contributions from wall deposits to the measured signal.[275] As will be discussed later, however, although the eventual deployment of the CHEM as a go/no-go tool for verifying the absence of HEU in cascade headers nominally satisfied the HSP's agreed specifications, to date, the CHEM has not seen extensive use, both due to the evolution of cascade technology, as well as usability issues with the system itself.

[273] D.A. Close, J.C. Pratt and H.F. Atwater, "Development of an Enrichment Measurement Technique and its Application to Enrichment Verification of Gaseous UF_6," *Nuclear Instruments and Methods in Physics Research A* 240 (1985): 398–405.
[274] P.L. Kerr et al., "IAEA Verification Experiment at the Portsmouth Gaseous Diffusion Plant: Report on the Cascade Header Enrichment Monitor," LA-13557-MS (Los Alamos National Laboratory, 1999) 4. https://www.osti.gov/scitech/servlets/purl/8200.
[275] Close, Pratt and Atwater, "Development of an Enrichment Measurement Technique and its Application to Enrichment Verification of Gaseous UF_6,"

At the London Group meeting, discussions over the Sydney Compromise conditions also continued. While the U.S. suggestions discussed earlier, including the exchange of intergovernmental notes on application of the HSP approach, were taken up without much discussion, the FRG still had concerns over the specifics of fulfilling the equal application condition, as well as security measures. Although the London Group had agreed on seven separate restrictions for in-cascade verification activities,[276] the FRG desired further commitments from the inspectorates regarding the handling of sensitive GCEP information, as well as a waiver of responsibility if information were to leak to unauthorized entities via inspection activities. To this end, the FRG suggested holding a special working group in mid-January 1983 to address the two Sydney conditions, but this suggestion was unanimously opposed by the other HSP participants.[277] The Troika nations, however, discussed these issues among themselves as the HSP came to a close.

Finally Fulfilling the Sydney Conditions

The conclusion of the London Group meeting, in essence, marked the end of negotiations on specific safeguards measures to be applied under the HSP, as well as fulfillment of the second Sydney condition. The LFUA measures negotiated in London would be formally approved by at

[276] These were:
a. The average frequency of inspection should be limited.
b. The number of inspectors participating in each inspection should be restricted.
c. The inspectors should be escorted.
d. The inspectors may not depart form the pre-determined and agreed paths.
e. The instruments and equipment to be used and the modalities of their use by inspectors are to be limited to those agreed upon.
f. The duration of the inspection activities may be limited to an agreed maximum time.
g. Access may be delayed by up to 2 hours.

Hexapartite Safeguards Project, "Inspection Activities…," (February 4, 1983), in R. Buttler et al., "Internationale Safeguards für Zentrifugenanlagen…," 28.

[277] Gerstler, "Multilaterales Kooperationsprogramm… Zusammenfassender Bericht der HSP-Sitzung vom 13.–16.12.…," PA AA, B 72 (ZA)/129441 (December 23, 1982), 7.

the seventh and final HSP meeting, held in Luxembourg from January 31–February 4, 1983, during which the definitive set of GCEP safeguards measures to be used, both inside and outside cascade areas, was agreed.[278] At this point, however, agreement had still not been reached as to how to satisfy the remaining two compromise conditions, which would be discussed among the Troika and among all HSP participants, ahead of the seventh HSP meeting, as well as after the project's formal end.[279]

Between the two outstanding conditions, the question of equal application was far easier to resolve, given that the issue was not clouded by substantive disagreements among HSP participants over any directly related topics, as the security condition was complicated by disputes over information classification between the Troika partners, and over the question of how to select IAEA inspectors. Furthermore, a path forward for fulfilling the condition had been agreed in London: the exchange of intergovernmental notes. By late December 1982, the UK had produced two draft templates for HSP States to use: a primary letter, in which each technology holder would endorse the LFUA approach, commit to its application under IAEA safeguards at existing and planned GCEPs within each State, and ask for a similar assurance from the addressee; and a reply letter to be used by each State for acknowledging receipt of each State's primary note.[280] Under the UK's plan, primary

[278] Hexapartite Safeguards Project, "Inspection Activities…," (February 4, 1983), in R. Buttler et al., "Internationale Safeguards für Zentrifugenanlagen…;" Joerg H. Menzel, ed. "Safeguards Approach for Gas Centrifuge Type Enrichment Plants," *Journal of Nuclear Materials Management* 12, no. 4 (1983): 30–37.
[279] An FRG BMFT brief from January 10, 1983 explicitly acknowledged that unity had been reached on safeguards measures, but not on equal application among technology holders and security issues. Original German: "Auf der letzten HSP-Sitzung (London, 13.–l7. Dezember 1982) konnte zwar zur Frage der Durchführung der Sicherungsmaßnahmen GUZ-Anlagen weitgehend Einigung erzielt werden. Dagegen steht Einigung über Erfüllung sonstiger Rahmenbedingungen - insbesondere gleichmäßige Anwendung bei allen Technologie-inhabern und Frage der sicherheitsmäßigen Behandlung - noch aus." Spilker to Auswärtiges Amt, "HSP: Rahmenbedingungen," PA AA, B 72 (ZA)/129441 (January 10, 1983).
[280] W. D. Evans to H.M. Spilker, "Hexapartite Safeguards Project," PA AA, B 72 (ZA)/129441 (December 29, 1983).

notes for each state were to be identical, save for a single paragraph describing each State's existing and planned GCEPs and the legal context for application of safeguards, using the HSP model, at those facilities.

The UK system for exchanging both primary and reply notes, along with its letter formats, was taken up by the HSP technology holders, albeit with some substantial changes. Initial amendments to the templates were raised in a Troika meeting held in mid-January 1983 that was held at the request of the FRG, in lieu of the additional FRG-proposed HSP ad-hoc meeting that had been rejected at the London Group meeting. At this meeting, the FRG voiced concern over the strength of the U.S. commitment to apply LFUA-type safeguards at Portsmouth.[281] Although the United States had publicly voiced its readiness to offer the Portsmouth GCEP for safeguards over the preceding year, the facility had not yet been added to the U.S. Eligible Facilities List (EFL) furnished to the IAEA under the terms of the U.S. VOA, and only planned on doing so "one year prior to the scheduled introduction of uranium into the first cascade,"[282] which was still a few years away. Furthermore, it was unclear for how long the IAEA would select the Portsmouth GCEP for safeguards. At the time, the IAEA would select a commercial fuel fabrication facility and two power reactors from the EFL and apply safeguards at those facilities for a period of two years, before rotating to another fuel fabrication plant and two different power reactors.[283] Applying this rotation principle to the Portsmouth GCEP, in the FRG's eyes, would be entirely unacceptable.

[281] Spilker, "HSP-Rahmenbedingungen: Troika ad-hoc Sitzung in London am 14.01.1983," PA AA, B 72 (ZA)/129441 (January 17, 1983), 1.
[282] G.W. Chantry to H.M. Spilker, "Hexapartite Safeguards Project," PA AA, B 72 (ZA)/129441 (January 24, 1983), 3.
[283] U.S. Department of State, "Agreement Between The United States of America and The International Atomic Energy Agency for the Application of Safeguards in the United States (and Protocol Thereto): Narrative," accessed September 21, 2017, https://www.state.gov/t/isn/5209.htm.

This FRG position was reinforced at the Troika meeting by the Netherlands, which saw a need for continued implementation of IAEA safeguards in nuclear weapon states.[284] Similar concerns were also raised by Japan, a few days later.[285]

Beyond the issue of application of LFUA safeguards at the Portsmouth GCEP, another question arose over the facilities to which technology holders' LFUA commitments would apply. Although the HSP had previously agreed that the only commercial-scale facilities were in the project's scope, it was unclear whether any commitments to LFUA should only apply to operating or planned facilities at the time of the HSP, or to all future plants.[286] While Japan was only willing to formally commit to LFUA application at currently operating facilities,[287] Australia advocated for covering all future plants.[288] These policy differences were reflected in early drafts of the country-specific paragraphs for each state. While Australia committed to "accept[ing] IAEA safeguards on any future commercial centrifuge uranium enrichment plant in Australia," and to "negotiate the appropriate facility attachment with the IAEA on the basis of limited-frequency, unannounced access by IAEA Inspectors to the cascade-halls in addition to the usual IAEA inspection activities outside the cascade halls," Japan wished to only explicitly commit to a facility attachment based on LFUA for Ningyo Toge, for domestic political reasons.[289]

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[284] Spilker, "HSP-Rahmenbedingungen…," PA AA, B 72 (ZA)/129441 (January 17, 1983), 1.
[285] W.D. Evans to H.M. Spilker, "Hexapartite Safeguards Project," PA AA, B 72 (ZA)/129441 (January 19, 1983).
[286] Ibid.
[287] Ibid.; G.W. Chantry to H. Spilker, "Hexapartite Safeguards Project," PA AA, B 72 (ZA)/129441, (February 24, 1983), 1.
[288] Evans to Spilker, "Hexapartite Safeguards Project," PA AA, B 72 (ZA)/129441 (January 19, 1983).
[289] Chantry to Spilker, "Hexapartite Safeguards Project," PA AA, B 72 (ZA)/129441, (February 24, 1983), 1.

Further discussions on the content of the intergovernmental letters took place at the seventh HSP meeting in Luxembourg. At this late stage in the project, however, negotiating uniform language on the applicability of LFUA to facilities in each State would have taken far too much time. Instead, the technology holders agreed to common language in the first paragraph of each note recognizing that LFUA was appropriate for NPT safeguards at GCEPs, writ large, while allowing for differing commitments to application of LFUA at current or future facilities in each State. Thus, although all technology holders would recognize the legitimacy of LFUA, commitments to implement LFUA at specific facilities varied by country, with LFUA commitments for some States being far more open-ended than others. The U.S. draft letter submitted at the seventh HSP meeting only referenced LFUA application at Portsmouth, and made no commitments regarding LFUA or safeguards eligibility of future commercial enrichment plants.[290] The common language, as agreed at the end of the seventh HSP meeting on February 4, 1983, read:

> "The Government of [State] has concluded that for the objectives of IAEA safeguards to be realised it would be appropriate for all commercial gas centrifuge uranium enrichment plants, situated in States Party to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) to be placed and to remain under an IAEA safeguards regime involving limited frequency unannounced access by IAEA inspectors to centrifuge cascade halls, as well as inspection activities outside the cascade halls, in accordance with the findings of the Hexapartite Safeguards Project."[291]

Progress was also made on securing a more definite commitment to LFUA application at the Portsmouth GCEP. Although the country-specific paragraph for the U.S. did not refer to

[290] The absence of a U.S. commitment to implement LFUA at plants other than the Portsmouth GCEP would become relevant during the commissioning of URENCO USA's GCEP in Eunice, New Mexico in the early 2010s, during which discussions on the nature of international safeguards at the facility took place. As the U.S. intergovernmental note only bound the United States to negotiate an FA featuring LFUA specifically at the Portsmouth GCEP, however, it was clear that LFUA was not obligatory at the URENCO USA facility.
[291] Hexapartite Safeguards Project, "Annex A (Incorporating amendments made at Luxembourg up to 5 pm 4 February," PA AA, B 72 (ZA)/129441 (February 4, 1983).

implementation of LFUA at any GCEP besides the one at Portsmouth, the five other technology holders inserted a paragraph into their notes, making their endorsement of the HSP's results contingent upon application of LFUA at Portsmouth. The specific language read:

> "If the Government of the United States of America is unable for any reason to complete in due time the requisite steps to place the commercial Gas Centrifuge Enrichment Plant at Portsmouth, Ohio on the eligible list for selection by the IAEA for application of safeguards, the Government of [State] may be obliged to reconsider its own position."[292]

By the end of the seventh HSP meeting, the substance of the intergovernmental notes, by in large, had been agreed. Nevertheless, a subsequent meeting was held in Vienna on March 14-15, 1983 to finalize the texts of the letters,[293] ahead of the formal exchange of notes, scheduled for April 20, 1983, over two and a half months after the conclusion of the HSP. In the meantime, Euratom had voiced its desire to provide its own note to the six technology holders, announcing its intention to negotiate FAs featuring LFUA for GCEPs in the FRG, the Netherlands, and the UK, pursuant to the 1973 IAEA-Euratom agreement, and the 1976 IAEA-Euratom-UK safeguards agreement.[294] In turn the IAEA also produced its own note acknowledging the findings of the HSP and confirming its willingness to negotiate FAs involving LFUA for GCEPs in all HSP States.[295] Besides the addition of the IAEA and Euratom letters, however, no substantive changes were made to the intergovernmental notes, although a separate exchange of notes was also planned between the USA, UK, and the IAEA, committing the IAEA to select Capenhurst and Portsmouth from their

[292] Ibid.
[293] The full set of intergovernmental notes is given in I.R. Kenyon to All Participants in HSP, PA AA, B 72 (ZA)/129441 (March 16, 1983).
[294] Chantry to Spilker, "Hexapartite Safeguards Project," PA AA, B 72 (ZA)/129441 (January 24, 1983), 1.
[295] Kenyon to HSP Participants, (PA AA, B 72 (ZA)/129441 (March 16, 1983), 4.

respective States' EFLs.[296] With the April 1983 note exchange, conclusion was reached over equal application of GCEP safeguards among the HSP participants.

Resolution of the security condition, by contrast, was more complicated, given the continuing dispute within the Troika over the sensitivity of classified information that could be leaked through LFUA, as well as the unresolved question of GCEP inspector nationalities. Both of these issues would, in fact, go unsettled through to the very end of the HSP.

The FRG raised fulfillment of the security condition at the mid-January 1983 Troika meeting, at which it presented a five-point statement on GCEP information protection to be given by all six HSP technology holders. The statement read:

1. "Governments, whose experts have participated in HSP, in view of their responsibility to protect sensitive information on the construction and operation of centrifuge uranium enrichment plants, are fully aware of the proliferation risks and commercial risks associated with LFUA.
2. They share the common objective that all necessary cautionary measures (e.g. accompanying of inspectors, limitation of information to be transmitted) have to be taken in order to minimize risks involved.
3. While respecting the independance [sic.] of the IAEA secretariat and the international character of the Agency, they will also draw the attention of the Director General to the security concerns with regard to the protection of sensitive information.
4. Regarding the selection of inspectors by the IAEA for performing LFUA at centrifuge uranium enrichment plants, Governments will furthermore seek informal ways to assist the Director General of the IAEA in the selection of his best qualified and dedicated staff for such missions, taking into account the particular proliferation and commercial risks involved.

[296] Per Fischer to FRG AA Staatssekretär, "IAEO; Abschluß der Beratungen über ein technisches Verfahren für die Anwendung von Safeguards in kommerziellen Urananreicherungsanlagen nach dem Gasultrazentrifugenverfahren in USA, GB, D, NL, Japan und Australien (Hexapartite Safeguards Project – HSP)," PA AA, B 72 (ZA)/129441 (March 24, 1983), 2–3.

5. Governments, in adopting LFUA, are conscious of the difficulties and risks involved in inspecting sensitive nuclear installations, like centrifuge uranium enrichment plants, even if all necessary cautionary measures have been taken."[297]

The main objective of the FRG statement was to establish collective responsibility among the HSP participants for the protection of proliferation-sensitive GCEP information, or more fundamentally, to deflect liability for the leakage of any sensitive information from any FRG (or Troika) facility. With each HSP technology holder formally acknowledging the risks inherent to LFUA, the FRG government could then argue that any security breaches via LFUA on FRG soil were due to a policy sanctioned not on its own volition, but also by five other States. Furthermore, this approach made irrelevant the question of determining the classification levels of information at risk, along with the need to reconsider the classification levels of that information. From the FRG's perspective, the choice was between downgrading the classification levels of at-risk information to Restricted or below, thus legitimizing its release to foreign nationals, or the more expedient option which it favored, to merely acknowledge that uncontrolled releases of classified information could occur, and that a collective responsibility existed among the HSP States to prevent this from happening. Although the UK and Netherlands did not criticize this statement in the meeting, however, the FRG plan was not endorsed.[298]

Over the next few months, following the seventh HSP plenary meeting, the FRG government attempted to persuade the United States to acknowledge the possibility of information compromise through LFUA, fearing that it could otherwise fall under U.S. accusations following a leak. With

[297] Draft Statement, January 13, 1983, Attachment 3 to Spilker, "HSP-Rahmenbedingungen…," PA AA, B 72 (ZA)/129441 (January 17, 1983).
[298] Spilker, "HSP-Rahmenbedingungen…," PA AA, B 72 (ZA)/129441 (January 17, 1983), 2.

this objective in mind, the FRG pushed further following a February 1983 JC meeting, during which the Troika agreed on measures for fulfilling the three Sydney conditions.[299] For meeting the security condition, the Troika decided to raise its concerns (primarily those of the FRG) in an oral demarche to the IAEA, and undertake a demarche to the United States to encourage its participation in the former.[300] The FRG took up the task of drafting a note verbale to be used in the IAEA demarche. Within days, however, the FRG also drafted another note verbale to be used in the Troika-U.S. demarche. Its language was far more forceful than that in the FRG's five-point statement, arguing that the only way to resolve avoid the compromise of classified information via LFUA implementation would be to pressure the IAEA Director General to "select his best qualified and responsible staff and to take the necessary administrative and security measures for the organization and functioning of his staff.[301]" To this end, the note requested the United States to make a demarche on information security to the IAEA in tandem with that of the Troika. Furthermore, the FRG note requested that the U.S. Government

> "[furnish the Troika] with a written communication that the United States Government is also aware of the possible conflict of interest between the necessary protection of sensitive information on commercial gas ultracentrifuge uranium enrichment plants and assuring the credibility of Agency safeguards by admitting Agency inspectors to the cascade halls of such plants."[302]

[299] Here, the Troika agreed that the equal application condition would be met by the intergovernmental note exchange, and that the codified set of HSP safeguards measures agreed in Luxembourg satisfied the condition on definition of inspection activities. See Tripartite Joint Committee, "Minutes of the Joint Committee Held in the Department of Energy London, on 11 February 1983, PA AA, B 72 (ZA)/129440 (February 11, 1983), 5–6.
[300] Ibid.
[301] "Draft Note Verbale," 2, attachment to Rouget, "IAEO, Safeguards in kommerziellen Urananreicherungs-Gasultrazentrifugen-Anlagen: Demarche der Troika gegenüber den USA," PA AA, B 72 (ZA)/129441 (February 23, 1983).
[302] Ibid.

The explicit aim of this request, as discussed internally within the FRG government, was to ensure that the United States would take on the political responsibility for any leaks disclosed via LFUA.[303]

The Netherlands criticized the FRG's approach. Of course, the Dutch position at the time was that information classified Confidential or above would not be revealed through LFUA activities, and so the Dutch government argued that the FRG statement on LFUA risking the disclosure of classified information was "factually incorrect."[304] In addition, the FRG's request for a written statement from the United States on the possible release of sensitive information was unpalatable to the Dutch, who argued that it would unnecessarily complicate the Troika's request, which only needed to ask for U.S. support for the Troika-IAEA demarche.[305] The UK, as JC chair for 1983 and thus tasked with delivering the Troika-U.S. demarche, heavily edited the FRG note verbale to meet the Dutch concerns, as well as input provided by the United States itself.[306] The new conditions for information protection used in the Troika-U.S. demarche merely stated that the three governments had agreed that information will be "adequately protected provided that (1) there is a clear definition of the scope and nature of the Inspectorate's activities; (2) that the IAEA takes all due precautions in accordance with INFCIRC 153 paragraph 5," which obligates the IAEA to

[303] Translated language in a March 7, 1983 position brief on the demarche reads: "The USA should… adopt the political responsibility (regarding nonproliferation) for the inspection measures that it supported." Original German: "die USA sollen… die NV-politische Verantwortung für das von ihnen durchgesetzte Inspektionsverfahren übernehmen. Rouget, "IAEO, Safeguards in kommerziellen Urananreicherungs-Gasultrazentrifugen-Anlagen: Demarche der Troika gegenüber den USA," PA AA, B 72 (ZA)/129441 (March 7, 1983), 2.
[304] "Netherlands Comments to the Draft Note Verbale for Troikaldemarche in Washington on the Heksapartite Safeguards Project, Early March 1983" (March 1, 1983), attachment to FRG Den Haag Diplo to Bonn AA, Telegram No. 136, PA AA, B 72 (ZA)/129441 (March 2, 1983).
[305] Ibid.
[306] British Embassy Bonn, "Speaking Note: Hexapartite Safeguards Project," ST 166/648/1 (March 8, 1983), attachment to Rouget to Loosch, PA AA, B 72 (ZA)/129441 (March 8, 1983).

protect confidential information that it obtains from States.[307,308] This language, in contrast with that proposed by the FRG, would not stir controversy between the Troika and the United States, given that it simply repeated one of the Sydney conditions, as well as a now long-standing IAEA obligation. This version of the note verbale was then delivered in a demarche by the UK, on behalf of the Troika, at the U.S. Embassy in London.[309] The FRG, nevertheless, may have approached the U.S. government informally at the same time, acting only on behalf of itself, to discuss liability for information breaches. A late March 1983 FRG AA memo on the outcome of the HSP states that the political responsibility for leaks of sensitive information will not be put placed upon the FRG, given the relationship between the FRG and the USA, in conjunction with the commitments to LFUA made in the intergovernmental notes and the demarche to the IAEA (which by then had taken place).[310] Nevertheless, it is unclear whether the United States ever explicitly adopted any

[307] Ibid., Annex I.

[308] INFCIRC/153, para. 5 states, "The Agreement should provide that the Agency shall take every precaution to protect commercial and industrial secrets and other confidential information coming to its knowledge in the implementation of the Agreement. The Agency shall not publish or communicate to any State, organization or person any information obtained by it in connection with the implementation of the Agreement, except that specific information relating to such implementation in the State may be given to the Board of Governors and to such Agency staff members as require [sic.] such knowledge by reason of their official duties in connection with safeguards, but only to the extent necessary for the Agency to fulfil its responsibilities in implementing the Agreement. Summarized information on nuclear material being safeguarded by the Agency under the Agreement may be published upon decision of the Board if the States directly concerned agree."

[309] British Embassy Bonn, "Speaking Note: Hexapartite Safeguards Project," attachment to Rouget to Loosch, PA AA, B 72 (ZA)/129441 (March 8, 1983).

[310] Original German: "Der Notenwechsel zwischen der Troika und den USA (plus Japan und Australien) über die gegenseitige Anerkennung der "continuing responsibility" für die Sicherheit der GUZ-Informationen und die britische Demarche im Namen der 6 Teilnehmerstaaten stellen jedoch im Verhältnis zwischen uns und den USA hinreichend klar, daß, wenn trotz aller Vorsichtsmaßnahmen durch IAEO-Inspektoren sensitive Informationen zur Kenntnis unerwünschter Regierungen gelangen, die politische Verantwortung hierfür nicht bei uns liegen kann." Per Fischer, "Abschluß der Beratungen über ein technisches Verfahren für die Anwendung von Safeguards in kommerziellen Urananreicherungsanlagen nach dem Gasultrazentrifugenverfahren in USA, GB, D, NL, Japan und Australien (Hexapartite Safeguards Project - HSP)" PA AA, B 72 (ZA)/129441 (March 24, 1983), 4.

responsibility for the future leakage of any GCEP information from the FRG, or from any other HSP technology holders.

Upon receiving U.S. backing, the UK also prepared to deliver the Troika demarche to the IAEA Director General, which was to take place in early April 1983.[311] Echoing the FRG's draft speaking notes, the note verbale for this demarche called upon the IAEA DG to select his "best qualified and responsible staff" for performing LFUA activities, and requested that he "take the necessary organisational, administrative and security measures to protect the information which will come into the Agency's possession as a result of inspections at gas centrifuge uranium enrichment plants."[312] After the text of the speaking note had been agreed with the United States, the Troika also invited Australia and Japan to associate themselves with the demarche, to demonstrate the consensus of HSP technology holders on the IAEA's responsibility to protect sensitive information. Both States accepted the offer, and the demarche was ultimately presented on behalf of all six HSP States.[313] With this final step, the Sydney condition on security had been satisfied.

[311] The FRG negotiation summary from March 24, 1983 stated that the demarche would take place after the British Standing Representative to the IAEA returned from the Preparatory Committee meeting for the UN Conference for the Promotion of International Co-operation in the Peaceful uses of Nuclear Energy (PUNE), which ran from March 28–April 8, 1983. See ibid., 3; United Nations General Assembly, "Addendum to the Report of the Preparatory Committee for the United Nations Conference for the Promotion of International Co-operation in the Peaceful uses of Nuclear Energy," Supplement No. 48A (A/37/48/Add.1) (1983), https://digitallibrary.un.org/record/48347/files/A_37_48_Add.1-EN.pdf.
[312] FRG Wien Inter to Bonn AA, Telegram No. 133, PA AA, B 72 (ZA)/129441 (March 17, 1983), 1–2.
[313] Fischer, "Abschluß der Beratungen…" PA AA, B 72 (ZA)/129441, (March 24, 1983), 3.

Post-HSP Questions

By mid-April 1983, HSP participants had mutually satisfied all three Sydney conditions, clearing the way for implementation of LFUA. This is not to say, however, that international safeguards for commercial GCEPs had been settled once and for all. Facility attachments needed to be drafted. No agreement had been made on how to divide verification activities between Euratom and the IAEA at Troika facilities. The Troika's internal information classification dispute was unresolved, and a system for IAEA inspector selection had still not yet been agreed.

Questions that arose during the drafting of GCEP FAs following the HSP demonstrate the minimal role that technical considerations played in the outcome of the HSP. By May 1983, a facility attachment for Capenhurst, covering joint IAEA-Euratom activities at all three cascade buildings (E21, E22A and the planned E22B plant), had been drafted. This draft FA called for four LFUAs per year at each plant, for a total of 12 LFUAs per year at the site.[314] During a Troika SOS meeting in early July 1983, however, the UK stated that it was unclear (given the results of the HSP) whether the Capenhurst FA should call for four visits per year to each plant's cascade hall (for a maximum of 12 LFUAs), or only four LFUAs to cascade halls within the plant as a whole each year.[315] Amazingly, this crucial detail on LFUA frequency had not been discussed during the HSP itself. Controversy also arose regarding the division of inspection effort between the IAEA and Euratom. While the Troika had understood that the safeguards measures negotiated under the HSP

[314] Euratom, "Safeguards Agreement in connection with NPT - Subsidiary Arrangements - Facility Attachment: QCAY," Annex, BArch, B 196/54363 (May 20, 1983).
[315] Tripartite Joint Committee, "Record of the Meeting of the Safeguards Sub-committee of the Centrifuge Joint-Committee Held at the Department of Energy on 6 July 1983," PA AA, B 72 (ZA)/129442 (July 6, 1983), 4.

would be carried out jointly by the two inspectorates, with effort divided equally between both, the Capenhurst[316] and Almelo draft FAs, as negotiated by Euratom, called for approximately thirty percent more inspection effort for Euratom over the IAEA.[317] The HSP's final document on GCEP verification activities, meanwhile, provided no explicit guidance on division of inspection effort between the two organizations.[318] Nevertheless, the HSP participants' formal acceptance of the credibility of GCEP safeguards with LFUA (in the intergovernmental letter exchange), with the inspection measures and frequencies that had been agreed upon, implied that Euratom need not undertake more effort than the IAEA in discharging its safeguards obligations. To this end, the FRG suggested to the SOS that the Troika request via a formal note that Euratom clarify that the HSP's results were a sufficient basis for its own verification, as well as IAEA-Euratom joint safeguards activities.[319] The UK, however, brought up the issue informally with Euratom through an oral discussion at first,[320] during which Wilhelm Gmelin, the new Euratom Safeguards director, argued that the extra effort was required for establishing Euratom's system of accounting and control for nuclear material (although Euratom had already established a system for its own safeguards activities starting in 1973).[321]

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[316] Euratom, "Safeguards Agreement in connection with NPT…," BArch, B 196/54363 (May 20, 1983).
[317] Tripartite Joint Committee, "Record of the Meeting of the Safeguards Sub-committee…" (July 6, 1983), 3.
[318] Hexapartite Safeguards Project, "Inspection Activities…," (February 4, 1983), in R. Buttler et al., "Internationale Safeguards für Zentrifugenanlagen…"
[319] I.R. Kenyon to Spilker, "Inspection of Urenco Centrifuge Plants in Light of HSP" (July 27, 1983), attachment to Spilker, "Troika - Joint Committee, London, 30. September 1983; TOP HSP-Follow-up," PA AA, B 72 (ZA)/129442 (September 16, 1983).
[320] Ibid.
[321] Tripartite Joint Committee, "Minutes of the Joint Committee held on 30 September 1983 at British Nuclear Fuels Ltd, Capenhurst," JC(1983) 2nd meeting, PA AA, B 72 (ZA)/129442 (September 30, 1983), 2–3.

While the Troika's dispute on information classification levels persisted through late 1983,[322] some progress was made on the inspector selection issue, in the months following the HSP's official close. At the core of the discussion still lay a fundamental tension between inspector capabilities and the likelihood of the disclosure of sensitive information. Highly competent inspectors, by nature of their training, could be more likely to gain and make use of commercially or proliferation sensitive information in carrying out LFUA activities. These inspectors would also be more likely to come from States with enrichment enterprises in competition with a GCEP operator, or with possible nuclear weapons aspirations. At the time, given these considerations, the Troika viewed inspectors from certain countries (e.g. Argentina, an NPT holdout with an enrichment program) as wholly undesirable.[323] Although the exclusion of inspectors of certain nationalities from a given facility was not precluded by INFCIRC/153, technology holders were aware that this was a politically delicate issue and could potentially attract accusations of unfair treatment from other States, who might perceive that the advanced GCEP technology holders had an unwarranted right to dictate terms of safeguards activities to the IAEA.[324] Second, some gray areas still existed: Euratom, which functioned as the nuclear material control authority for its members, held the only formal authority to approve or deny IAEA inspector designees, and so Member States had to influence inspector designee choices by working informally through Euratom. Furthermore, IAEA inspectors were not designated to specific facilities, but to States (or, in the case of the IAEA-Euratom safeguards agreement, to regions). At the time, only a single list of IAEA inspectors

[322] Spilker, "Troika - Joint Committee, London, 30. September 1983; TOP HSP-Follow-up," PA AA, B 72 (ZA)/129442 (September 16, 1983), 3–4.
[323] Tripartite Joint Committee, "Record of the Meeting of the Safeguards Sub-committee…" (July 6, 1983), 1.
[324] Ibid.

existed for all facilities within Euratom States,[325] and a separate list would need to be informally created for GCEP safeguards inspectors.

By July 1983, the JC SOS was considering two frameworks for inspector selection. The first concept involved creating a list of "approved" nationalities that technology holders were willing to receive in their facilities. Within this framework the Troika considered basing its list of nationalities on reciprocity, particularly among HSP partners: fears of leaking information to potential competitors (e.g. Japan) could be mitigated if British, Dutch or West German nationals were also conducting LFUA inspections at Ningyo Toge.[326] In the future, if other States (such as the Soviet Union) were to put enrichment plants under safeguards, then nationals of those States could also participate in LFUA at Urenco facilities. However, Troika representatives also recognized that some capable inspectors came from States without enrichment plants, and that did not pose a proliferation risk. An FRG representative pointed out that citizens of Eastern European States could be acceptable, and that instead of universally applying reciprocity between technology holders, GCEP States could instead select inspectors on an 'ad personam' basis, considering the qualifications and potential security risks associated with individual inspectors. Inspectors from all Euratom countries could be selected on a similar basis.[327] Both of these principles gained traction with the Troika and were tabled for discussion at subsequent SOS meetings.

The Tripartite JC discussed inspector selection at a meeting on September 30, 1983. By this time, the SOS had endorsed the reciprocity principle among HSP technology holders, and the United

[325] Ibid., 1–2.
[326] Ibid., 1.
[327] Ibid., 1–2.

States had given cursory approval to the concept. Plans were made to approach Japan on the margins of the IAEA General Conference, which was to be held on October 10-14, 1983.[328] In the meantime, the UK, as JC chair, had undertaken to approach the IAEA Director General concerning both the reciprocity and ad-personam principles,[329] putting into motion an informal system for the pre-screening of IAEA GCEP inspectors.

Reflections

After over a decade of talks, agreement on an international safeguards approach for gas centrifuge enrichment plants had finally come to pass.

The HSP's course on the misuse verification issue, and ultimate success, were politically driven. Prior to the HSP, constructive technical-level dialog on GCEP misuse verification under IAEA safeguards had been nearly impossible, owing to disputes over the interpretation and scope of INFCIRC/153, which led to the breakdown over cascade access in the late 1970s. This political logjam necessitated the creation of the HSP as a dedicated forum for designing a set of GCEP safeguards measures that would be acceptable to inspectorates, State technology holders, and facility operators. But while the HSP was nominally a technical forum, in reality, the project was above all designed to address the political problems over misuse verification that had made agreement on GCEP safeguards measures so elusive. Addressing these problems required political solutions.

[328] Tripartite Joint Committee, "Minutes of the Joint Committee held on 30 September 1983 at British Nuclear Fuels Ltd, Capenhurst" PA AA, B 72 (ZA)/129442 (September 30, 1983), 3.
[329] Tripartite Joint Committee, "Record of the Meeting of the Safeguards Sub-committee…" (July 6, 1983), 2.

This is not to say, however, that technical considerations were altogether ignored in the HSP. Substantial amounts of technical information were exchanged and discussed during the project. During the HSP's first year, while Team 4's work was intensely political, Team 3's work on developing material accountancy practices for verifying non-diversion progressed without strong disagreements or strife.[330] In the second year of the HSP, after the issue of undeclared feed had been resolved, objective discussions on possible facility misuse modes and verification measures became more prominent.

Addressing misuse verification, however, required a series of political compromises, which ultimately led to the creation of LFUA as a politically crafted tool that both satisfied the IAEA's needs for effective and efficient safeguards (although technical standards for effectiveness and efficiency were not set in this case), and also satisfied technology holders' concerns over security, equity in safeguards application, and the scope of INFCIRC/153-type safeguards. Although technical considerations were important, political dynamics played the primary role in the creation of misuse verification measures, first in reaching agreement on LFUA, and then in defining inspection activities. Agreement on LFUA required a series of political compromises. In the HSP's first year, the Troika had to reach a common position on how to treat undeclared material and activities. Although an understanding on giving "minimum recognition" to these issues was reached in Boekelo in March 1981, the Troika still struggled to maintain unity over the following months. Discord over undeclared material and activities would be largely put to rest in November 1981, via another political compromise orchestrated during the 4th HSP Plenary in Tokyo, whereby

[330] Interview with U.S. safeguards expert (September 27, 2017).

all parties agreed not to explicitly address these issues. LFUA implementation was predicated on a political compromise agreed at the 5th Plenary in Sydney. Key LFUA parameters, including cascade access frequency and NDA use, were agreed via political compromise themselves. In short, LFUA was a mostly political solution to a mostly political problem.

None of this analysis implies that the HSP should have somehow embarked on a more technically oriented course, or that LFUA is intrinsically deficient because it was not purely technically motivated. Given the highly charged context in which the HSP took place, the mere fact that the HSP produced a mutually acceptable agreement should be deemed a major success. If the HSP were to have failed, it is likely that the status quo would have continued, with ad-hoc inspections without cascade access at Almelo, and with non-access approaches implemented at Ningyo Toge and Gronau, to the detriment of safeguards effectiveness. Under these conditions, it is not unreasonable to imagine the Netherlands subsequently unilaterally negotiating an Almelo FA, putting the Treaty of Almelo in jeopardy. Without a precedent established, cascade access for IAEA inspectors would become a point of contention in every GCEP FA negotiation from then on. The precedent that LFUA set on cascade access, thus, is highly valuable.

This chapter has, in granular detail, explored the factors and events that led to its creation of the LFUA approach for GCEP misuse verification. At this point, the politically-determined origins of LFUA should be clear. This assessment can and should inform considerations on the state of GCEP misuse verification in the present day, and on what should be done in the future. Before discussing any next steps for GCEP safeguards, however, it is necessary to also understand how international GCEP safeguards needs and capabilities have changed since the end of the HSP. The next chapter

begins to address this question by assessing the technical effectiveness of the LFUA approach at the time it was conceived, and by discussing how GCEP misuse verification measures—particularly those that address HEU production—have evolved since the end of the HSP.

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Chapter 7 – Bridging the Hexapartite Safeguards Project and Contemporary Gas Centrifuge Enrichment Plant Safeguards

The Hexapartite Safeguards Project (HSP) approach for gas centrifuge enrichment plant (GCEP) safeguards is now almost thirty-five years old. In this period of time, gas centrifuge technology has gone from being an entrant in a global commercial uranium enrichment market dominated by gaseous diffusion technology to total dominance in the very same market today. Urenco's global capacity, now housed at the Almelo, Capenhurst, Gronau plants as well as a new plant in Eunice, New Mexico, has grown from approximately 1,000 tSWU/a at the end of 1983[1] to 18,800 tSWU/a at the end of 2016, with about 80% of the capacity growth taking place since the year 2000. In France, the Eurodif commercial gaseous diffusion plant (GDP) has been replaced by the Georges Besse II GCEP, which began operation in 2011, and achieves a nominal capacity of 7,500 tSWU/a using Troika technology. With the closure of the Paducah GDP in 2013, operated by the now-defunct U.S. Enrichment Corporation (USEC), commercial-scale gaseous diffusion enrichment came to an end. Although gaseous diffusion was a proven technology, over the final two decades of the 20th century, centrifugation had demonstrated itself to be reliable, while requiring approximately an order of magnitude less energy to operate. Furthermore, without bulky diffusion chambers, GCEPs required far less physical space than GDPs of equivalent capacity. Today, centrifugation constitutes the only economically viable means for uranium enrichment. Global

[1] R.B. Kehoe, *The Enriching Troika: A History of Urenco to the Year 2000* (Marlow, UK: Urenco Limited, 2002), 173.

enrichment demand, at approximately 50,000 tSWU/a, is now almost entirely satisfied by the gas centrifuge process.[2]

As GCEP technology grew into mainstream use, and as the international safeguards system began undergoing significant changes from the early 1990s onwards, the implementation of GCEP safeguards has also evolved. With some notable exceptions,[3] the HSP approach still serves as the primary standard for IAEA and Euratom safeguards (where relevant) at commercial GCEPs. While some key aspects of the HSP safeguards approach, in particular the implementation of material accountancy, have not changed dramatically, measures for verifying the absence of misuse have undergone substantial development. Novel NDA techniques for verifying header enrichment levels in real time have been developed, as well as environmental sampling techniques to detect the presence of highly enriched uranium (HEU) in process areas. Verification of the absence of undeclared feed is now explicitly treated as an IAEA GCEP safeguards objective. Despite efforts to bolster the ability of inspectorates to detect GCEP misuse, however, little has been done in practice to improve HEU production detection, which constitutes the most critical element of

[2] World Nuclear Association, "Uranium Enrichment," updated May 2017, accessed November 13, 2017. http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment.aspx.

[3] Exceptions include a specific safeguards approach for Chinese GCEPs featuring Russian-supplied centrifuges that was also developed in the 1990s, as well as a facility-specific approach for the Resende GCEP in Brazil, which falls under the Quadripartite Agreement between the IAEA, the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC), Brazil, and Argentina, which functions as the comprehensive safeguards agreement for the two nations. Safeguards provisions for the Iranian Pilot Fuel Enrichment Plant and Fuel Enrichment Plant in Natanz, Iran, both of which are far lower in capacity than modern and historical commercial facilities, are governed by the Joint Comprehensive Plan of Action (JCPOA) agreed in July 2015. For details on IAEA safeguards at Chinese plants equipped with Russian centrifuges, see A. Panasyuk et al., "Tripartite Enrichment Project: Safeguards at Enrichment Plants Equipped with Russian Centrifuges," IAEA-SM-367/8/02, Proceedings of the 2001 IAEA Safeguards Symposium (Vienna: International Atomic Energy Agency, 2001). On safeguards at Resende, see Sharon A. Squassoni and David Fite, "Brazil as litmus test: Resende and restrictions on uranium enrichment," *Arms Control Today* (October 2005).

GCEP safeguards. This chapter supports this argument by tracing the development of GCEP misuse verification measures from the end of the HSP in 1983, up to the present day.

Evaluating the Technical Effectiveness of the HSP GCEP Safeguards Approach

Before embarking on a discussion of how GCEP safeguards have evolved since the HSP, it is useful to first establish the set of measures that were agreed by the project, and to evaluate their technical effectiveness in the original context in which they were conceived. Doing so provides valuable perspective on the current state of GCEP safeguards needs and capabilities (which will be discussed in Chapter 8), vis-à-vis the state of GCEP safeguards effectiveness in 1983. This section addresses this task.

The HSP safeguards approach, as agreed at the end of the seventh HSP plenary meeting, is organized into two sections: one dealing with measures that are applied outside cascade areas, and the other with those that take place within cascade areas.[4] Between these two categories, measures undertaken outside cascade halls primarily address material accountancy, and activities inside cascade areas expressly address misuse, defined as "production of a significant quantity of uranium at an enrichment level higher than declared."[5] Verification of the absence of undeclared feed is not explicitly addressed in the HSP approach.

[4] Hexapartite Safeguards Project, "Inspection Activities Associated with Limited-Frequency unannounced Access Model Applied to Gas Centrifuge Type Enrichments Plants," (February 4, 1983) in R. Buttler et al., "Internationale Safeguards für Zentrifugenanlagen: Konzepte und Verfahren zur Kernmaterialüberwachung und das internationale Hexapartite-Projekt," Jül-Spez-216 (Jülich: Kernforschungsanlage Jülich, August 1983).
[5] Ibid., 10.

Inspection activities outside cascade areas, as agreed by the HSP, conform to those prescribed for material accountancy, via material balance evaluation, in INFCIRC/153. As at any nuclear fuel cycle facility under safeguards, inspectors were authorized to examine operating records and to evaluate the operator's measurement system for calculating inventory changes, physical inventory, and for calculating Material Unaccounted For (MUF).[6] Verification of nuclear material flows (during interim inventory inspections) is accomplished through identification and weighing of UF_6 cylinders and other containers, either using scales provided by the facility or by the inspectorate. ^{235}U flows are verified via destructive analysis from samples drawn from UF_6 containers and process streams, and through more frequent (but less accurate) non-destructive assay (NDA) measurements on UF_6 cylinders and other containers. Furthermore, the HSP approach explicitly mentions the use of in-line monitors outside cascade halls to measure ^{235}U enrichment in liquid and gaseous streams of UF_6 for verifying material flows.[7] Consistent with application of safeguards in other facility types, containment and surveillance (C/S) is used to support flow verification. Under the HSP approach, this is mainly done via application of seals, both on a temporary basis (during inspections), and on a longer-term basis. Temporary C/S activities might be undertaken in feed/withdrawal (F/W) areas to prevent containers being clandestinely moved or sealed in F/W stations during inventory verification, or at the cascade area boundary during LFUAs to prevent secret movements of material or objects. In the long term, seals can be applied on various objects, including cylinders, and on agreed valves and flanges on UF_6 pipework, "if so agreed and specified in the Subsidiary Arrangements."[8] Application of seals may be used for maintaining continuity of knowledge on UF_6 cylinder weights, and to indicate potential inventory

[6] Ibid., 21.
[7] Ibid., 22.
[8] Ibid., 16, 17.

changes. Once a container arrives in a GCEP cylinder storage area, the operator will weigh the cylinder, and record a change in the book inventory for the storage MBA. During the next interim inventory verification visit (IIV) inspectors may then verify the weight and enrichments of UF_6 in cylinders that have arrived since the last inspection, and subsequently seal them. Unbroken seals on containers indicate that no changes in book inventory should be associated with those containers since emplacement of the seals, and also allow the IAEA to verify the most recent book inventory change associated with each cylinder at a later time. Operators may break seals for legitimate purposes, including material sampling, cylinder homogenization, blending, or feeding material into the enrichment process itself.[9] Thus, in the context of sealing UF_6 cylinders, broken seals do not necessarily imply malicious activity: instead, they merely indicate to inspectors that a book inventory change associated with a cylinder should be expected. Physical inventory verification (PIV), which is implemented at essentially every facility under international safeguards, makes up the final element of activities outside cascade areas under the HSP approach. For a 1000 tSWU/a facility, the HSP participants expected an annual operator physical inventory taking (PIT) followed by PIV (in line with the annual one-year timeliness goal for LEU), which would take about two weeks to perform. Throughout the year, routine IIVs would take place in approximately monthly intervals (12–15 times per year for a 1000 tSWU/a facility), with each visit lasting approximately 3 working days.[10] The target detection objectives for LEU diversion from a GCEP have been stated to be one significant quantity (SQ) of LEU (75 kg ^{235}U) within one year, with a detection probability of 50%.[11]

[9] Buttler et al., "Internationale Safeguards für Zentrifugenanlagen…," 91–92.
[10] Hexapartite Safeguards Project, "Inspection Activities…," (February 4, 1983), in R. Buttler et al., "Internationale Safeguards für Zentrifugenanlagen…," 26.
[11] Brian D. Boyer, "Safeguards Approaches for Gas Centrifuge Enrichment Plants," LA-UR-08-03736 (Los Alamos National Laboratory, July 1, 2008), 19.

For inspection activities within cascade halls—for the purpose of detecting facility misuse—verification measures were clearly more avant-garde in that they were mostly superfluous to the task of material accountancy, although INFCIRC/153-type safeguards agreements still provided sufficient legal authority for inspectors to perform these activities. In the HSP's approach, as agreed at the seventh plenary meeting, description of measures used within cascade areas (i.e. those to be used during LFUAs) are divided between visual observation and technical measures to be applied at both routine and initial inspections.

During an initial cascade area inspection, a key goal entails determining the 'transparency' characteristics of the enrichment equipment. As agreed in late 1982 (and as discussed in the previous chapter), the nature of LFUA activities were to depend on plant design: Troika plants at the time featured a "repetitive design," in which cascades were individually connected to unit headers via externally observable valves, whose positions could be verified to ensure that cascades were not being connected in series.[12] In these plants, visual observation activities would take precedence over technical measures, as it was believed that cascade modifications and rearrangements would be readily visible to inspectors, particularly if compared with design drawings or photographs taken previously. Photographs and design drawings would be collected during this visit. Technical measures, in this case, would be limited to cascade header enrichment measurements, to be taken with the to-be-developed Cascade Header Enrichment Monitor (CHEM) system. Conversely, American equipment displayed lesser 'transparency' features, impeding visual verification of cascade plumbing. For these plants, instrumentation, in particular

[12] Hexapartite Safeguards Project, "Inspection Activities…," (February 4, 1983), in R. Buttler et al., "Internationale Safeguards für Zentrifugenanlagen…," 17.

the four NDA techniques developed by the U.S. national laboratories, would take precedence over visual observation during LFUAs. Overall, the goal in distinguishing between transparency characteristics was to ensure that the equal benefit could be derived from unannounced visits to cascade areas.[13] In addition to determination of facility transparency, an initial cascade visit would also be used to determine possible applications and locations for technical measures.

Visual observation, under the HSP approach, first entails verifying that "nuclear material contained in the cascade area is as declared." This language could be interpreted as an acknowledgement of the possibility of undeclared feed but was likely interpreted at the time to allow for verification of any items (such as sample containers) inside the cascade hall. Nevertheless, this is not to say that that visual observation during LFUAs was not useful for detecting undeclared material: as with during activities outside cascade areas, there would exist the possibility that inspectors could discover an undeclared container of UF_6 in a cascade hall, even though the intended purpose of LFUA inspections was not to do this. Second, inspectors verify "safeguards relevant installed equipment, process configuration and plant features" by comparing observations with previously obtained design drawings, photographs, and other records. Third, inspectorates verify that all piping containing nuclear material passes through declared penetrations at the boundary of the cascade area, and ends at declared points, as documented in the facility design information.[14]

Technical measures are divided into three categories: radiation monitoring, sampling, and use of seals. The extent of radiation measurements depends, as mentioned earlier, on the transparency characteristics of the cascade equipment. Stationary or portable radiation detectors and NDA

[13] Ibid., 25–26.
[14] Ibid., 24.

equipment may be used, even though only portable devices (such as the CHEM) were initially employed, with continuous monitoring equipment first installed in GCEPs in the early 1990s.[15] The HSP approach provides for direct sampling of UF_6 from cascades, although in practice, inspectorates have not frequently exercised this opportunity,[16] likely owing to the time and equipment involved. As the duration of an LFUA may be "limited to an agreed maximum time,"[17] drawing a gas sample would consume valuable time that could be devoted instead to searching for indicators of misuse throughout the cascade hall, instead of focusing in on a specific point in a cascade or a cascade header. HSP participants agreed that the time required for performing an LFUA inspection would range between one and eight hours.[18] Finally, inspectorates have the opportunity to apply seals to valves or flanges inside cascade areas, if they are normally kept in one state (open or closed), and to verify them on subsequent visits. In cases where valves are remotely manipulated and concealed entirely within cascade piping, however, sealing techniques provide little utility.

[15] INFCIRC/153 offers the IAEA considerable flexibility in the types of equipment and measurements that it may employ during, and for the purposes of, inspections. Paragraph 74, which elaborates on the scope of IAEA inspections, allows the IAEA to "make independent measurements of all nuclear material subject to safeguards under the Agreement" (para. 74(b)) and to "apply and make use of surveillance and containment measures" (para. 74(c)) without elaborating on types of equipment to be used, and paragraph 74(e) allows the IAEA to "use other objective methods which have been demonstrated to be technically feasible." Thus, while technical measures must conform to other important undertakings, such as minimization of disruption to facility operations, and protection of sensitive information, there exist essentially no restrictions in INFCIRC/153 on the nature of technical measures itself. See "The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons," INFCIRC/153 (corrected) (Vienna: International Atomic Energy Agency, June 1972).
[16] Boyer, "Safeguards Approaches for Gas Centrifuge Enrichment Plants," 24.
[17] Hexapartite Safeguards Project, "Inspection Activities…," (February 4, 1983), in R. Buttler et al., "Internationale Safeguards für Zentrifugenanlagen…," 28.
[18] Ibid., 27.

Although LFUA frequency was determined politically, with the lower frequency limit established upon the insistence of the FRG HSP delegation,[19] quantity and timeliness goals consistent with the agreed 4–12 inspections/year frequency were established. The assumed misuse strategy under the HSP would involve modifying of equipment to produce HEU, production of HEU containing 25 kg of ^{235}U, diversion of the material, and then restoration of facility equipment to its original condition. A German report published shortly after the end of the HSP notes that participants deemed it necessary to detect this scenario within 1–3 months,[20] which is precisely consistent with the agreed LFUA frequency of 4–12 inspections per year, assuming that evidence of misuse could be detected after the fact. However, no detection probability goal is explicitly defined for detection of excess enrichment levels or HEU production. The only reference in the HSP to a detection probability target for misuse is that the safeguards approach should offer "high confidence" in the absence of misuse:

> "implementation of the objective of safeguards entails a set of safeguards measures whose application by the Inspectorate(s) permits the detection, in a timely manner and with ***high confidence***, of the diversion of a significant quantity of uranium, including the production of a significant quantity of uranium at an enrichment level higher than declared."[21] [emphasis added]

[19] In internal minutes from the December 1982 London HSP meeting, during which LFUA measures was agreed, Gerstler, wrote "we formally insisted on 4 [inspections] per year on the basis of the JC decision and technically on the basis of the frequency of [inspections] in external areas, which at this time in Almelo are already at twelve per year." Original German: "Wir bestanden formal mit Hinweis auf JC-Entscheidung und technisch mit Hinweis auf Frequenz des Außenbereiches, die in Almelo z.Z. bereits bei 12/Jahr liegt, auf 4/Jahr." Gerstler, "Multilaterales Kooperationsprogramm Kontrollmaßnahmen für GUZ-Anlagen "Hexapartite-Safeguards-Project: Zusammenfassender Bericht der HSP-Sitzung vom 13.–16.12. in London," PA AA, B 72 (ZA)/129441 (December 23, 1982), 4.
[20] Buttler et al., "Internationale Safeguards für Zentrifugenanlagen…," 128.
[21] Hexapartite Safeguards Project, "Inspection Activities…," (February 4, 1983), in R. Buttler et al., "Internationale Safeguards für Zentrifugenanlagen…," 10.

No elaboration is made on the term “high confidence.”

While the precise detection probability sought by the HSP is unclear, a detection probability for production of one significant quantity (SQ) of HEU at a 1000 tSWU/a GCEP can be estimated using Equation 2.11 from Chapter 2. Using division of the raw numbers, it can be estimated that it would take about 1.8 days for a 1000 tSWU/a facility to produce the necessary separative work (about 5 tSWU) to produce about 25 kg of ^{235}U in HEU using natural uranium feedstock (assuming that no pre-enriched LEU feedstock is available). This estimate, however, is unrealistic, as it assumes that the entire nominal separative capacity of the facility can be arranged into a single ideal cascade, in effect. In reality, GCEPs are organized into units that cannot be readily piped together, and constraints also exist on how individual cascades can be practicably rearranged within units. When these restrictions are considered, it is apparent that considerably more time is required. As will be shown in Chapter 8, facility design constraints approximately double this amount of time. Assuming a production time of four days, and another 3 days each for facility modification and restoration (assuming that centrifuges could be kept running during the reconfiguration process), we can estimate that a facility misuse episode would last about ten days. Assuming a 0% false negative rate, 4–12 LFUAs per year imply a detection probability of 10–28%, if a ten-day breakout were to occur at any time in a given year. Of course, primary evidence does not indicate that the HSP deliberately sought out a detection probability in this range. Instead, HSP participants seem to have settled on a timeliness goal of 1–3 months and assumed that any misuse could be detected after it had taken place. Euratom Safeguards Director Wilhelm Gmelin highlighted this assumption in 1997, when he wrote,

"[s]afeguards at enrichment plants had been based on several assumptions or "acts of faith" following the conclusions of the Hexa-Partite-Safeguards Project in 1983:

- Changing cascades for HEU (>20%) production from LEU production require physical reconfiguration of such cascades;
- Such reconfigurations could be detected effectively by the inspectorates when deploying the LFUA (Limited Frequency Unannounced Access) regime;

Euratom accepted the HSP conclusions at the time, inter alia, due to the need to minimize proliferation of sensitive technology."[22]

Besides possible discrepancies in material accountancy data that could take weeks or months to resolve, it is unclear how evidence of misuse would be uncovered, post-facto, if an operator were to restore equipment to its original configuration after a misuse episode, and before the next LFUA visit. Environmental swipe sampling, which could uncover HEU production via isotopic assay of particles deposited near breaches in UF_6 piping (i.e. around valves, sampling points, and feed/withdrawal connection points), was not yet available for safeguards use. Thus, a case can be made that the LFUA frequency agreed by the HSP did not lend itself to particularly robust verification with respect to timely detection, given that an SQ of highly enriched UF_6 could easily be converted into metallic form for weapon component fabrication in a small-scale, easily concealable clandestine conversion facility, following its diversion from a GCEP. Nevertheless, a detection probability of 10–28% for production of a single SQ of 90%-enriched material within one year could provide a substantial deterrent to a risk-averse actor, so it may also be argued that despite its predominantly political origins, LFUA did offer a substantial safeguards capability.

[22] W. Gmelin, "Safeguards Policy and Technical Methodology from the Euratom Perspective," Proceedings of the 38th Annual Meeting of the Institute of Nuclear Materials Management (Phoenix, AZ, 1997), 4.

Since the HSP ended, plants not only grew in capacity, but also acquired new capabilities that challenged assumptions on proliferation potential made during the HSP. As GCEP technology progressed, however, GCEP technology holders were able to make informal technical arrangements with inspectorates to improve misuse verification measures to keep pace with these developments. While often unsuccessful, this process nevertheless contrasts with the formal, consensus-driven approach adopted in the 1970s through the HSP, which brought so much discord to the fore. The following section discusses how this evolution developed.

The Evolution of GCEP Safeguards, 1983–Present

1. Cascade and Unit Header Monitoring

Over the years since the HSP concluded, three new NDA devices were developed for measuring UF_6 in cascade and unit headers, and approved for international safeguards use: the CHEM, the Continuous Enrichment Monitor (CEMO), and the On-Line Enrichment Monitor (OLEM). Each of the latter two systems featured improvements over previously designed systems. However, rollout of these devices was often far from seamless, owing both to technical and political factors, and none of these systems found use in more than a small handful of facilities.

The CHEM system, despite its creation at the insistence of the Troika during the HSP, would never see widespread deployment at GCEPs. Development of the CHEM was carried out after the HSP by the United States at Los Alamos National Laboratory, and in October 1985, a paper was

published in *Nuclear Instruments and Methods in Physics Research A*[23] describing the CHEM's measurement technique. However, half a decade passed between the publication of this paper and implementation of the technique, which only took place at Ningyo Toge and Capenhurst beginning in 1990.[24] At Almelo and Gronau, considerable problems were encountered with the CHEM, owing to the different material constitution of cascade header pipes at those facilities.[25] At Gronau, it was further reported that low gas pressure in the cascade headers, small pipe diameters, and long measurement times confounded the use of the CHEM.[26] Pipe wall deposits bearing UO_2F_2, which is a product of UF_6 hydrolysis, as well as thorium from uranium decay, compounded difficulties with CHEM. Because the CHEM relies on the use of a physical collimator to measure and subtract the effect of pipe deposits, differently sized pipes each require a custom collimator to fit their specific geometries—and in the case of small pipes, designing a suitable collimator may be impossible without masking too much detector area. By late 1987, Urenco reported that NDA measurements had still not yet been conducted during LFUAs at its facilities in continental Europe.[27] Furthermore, Urenco argued that since LFUA activities had been successfully carried out for two years at Almelo and Gronau, it was worth questioning whether enrichment measurements on header pipes would actually be useful at all for safeguards. Even at Capenhurst,

[23] D.A. Close, J.C. Pratt and H.F. Atwater, "Development of an Enrichment Measurement Technique and its Application to Enrichment Verification of Gaseous UF_6," *Nuclear Instruments and Methods in Physics Research A* 240 (1985): 398–405.
[24] D.W. Swindle, "Realities of Verifying the Absence of Highly Enriched Uranium (HEU) in Gas Centrifuge Enrichment Plants," Proceedings of the 1990 March Meeting of the American Physical Society (Anaheim, California, March 12-16, 1990), 11.
[25] Interview with German safeguards expert, November 27, 2016.
[26] Mark D. Laughter, "Profile of World Uranium Enrichment Programs—2009," ORNL/TM-2009/110 (Oak Ridge National Laboratory, 2009), 15.
[27] E. Steinebach and B.G. Dekker, "Safeguards at the Dutch and German Uranium Enrichment Plants of URENCO – Development and Experience," Proceedings of the 3rd International Conference on Facility Operations-Safeguards Interface (San Diego, CA, November 29-December 4, 1987), quoted in Adam Shephard, "*Process Attribute Monitoring Approach to Gaseous Centrifuge Enrichment Plant Safeguards*" (PhD diss., The University of Tennessee, 2016), 70.

the CHEM's utility was hampered by extremely lengthy measurement times, which could be as long as eight hours,[28] owing to the low radiation signal from the low-pressure gas in cascade headers. As this amount of time equals the maximum allowable time under an LFUA, it can be argued that a CHEM measurement may not be the most efficient use of inspectors' time during an LFUA. In 2006, the IAEA noted that the use of CHEM, as designed, results in a "rather low detection probability,"[29] because so few measurements can feasibly be carried out in the allowable time. Furthermore, the CHEM's employment of x-ray fluorescence (XRF) as a measurement technique necessitated the use of a ^{57}Co radiation source with a 272-day half-life, requiring frequent replenishment. In sum, the CHEM was not conducive to the efficient implementation of safeguards.

The CHEM nevertheless found routine use in Japan, where it was employed at the now-decommissioned Ningyo Toge pilot facility and demonstration plants from 1990 onwards,[30] and is used, as of February 2016,[31] at the Rokkasho enrichment plant. Although the CHEM's fundamental shortcomings remained through its first two decades of use, with respect to its short-lived radiation source, measurement time and pipe geometry sensitivity, the CHEM system, then only in use at Japanese facilities, was upgraded in the late 2000s[32] as new detector technology became available. The upgraded CHEM featured an electromechanically cooled high-purity germanium (HPGe)

[28] Interview with U.S. safeguards expert, June 27, 2016.
[29] W. Bush et al., "Model safeguards approach for gas centrifuge enrichment plants," IAEA-CN-148/98, Proceedings of the 2006 IAEA Safeguards Symposium (Vienna: International Atomic Energy Agency, 2006), 622.
[30] Swindle, "Realities of Verifying the Absence of Highly Enriched Uranium (HEU)…," 11.
[31] Shephard, "*Process Attribute Monitoring Approach…*," 59.
[32] J.N. Cooley et al., "Model Safeguards Approach and Innovative Techniques Implemented by the IAEA at Gas Centrifuge Enrichment Plants," Proceedings of the 48th Annual Meeting of the Institute of Nuclear Materials Management (Tuscon, AZ, 2007).

detector for measuring XRF lines, replacing the old system's sodium iodide (NaI) detector.[33] This served to improve measurement accuracy via better detector energy resolution, and decrease measurement times.

At European facilities, however, use of the CHEM was short-lived. By the early 1990s, the CHEM was already challenged by its intrinsic technical shortcomings, but also by the development of new Troika-developed enrichment technology. Urenco's new flexible cascade technology, which was rolled out almost immediately after CHEM was implemented at Capenhurst, ultimately precipitated its downfall, which led to its succession by the Continuous Enrichment Monitor (CEMO). Development of this new cascade technology took place amidst a revival of tripartite R&D collaboration that began to take shape almost immediately after the conclusion of the HSP.[34]

After an initial decade of centrifuge technology R&D overseen separately by individual Troika States, in the early 1980s, Urenco put in place a long-term plan to standardize its technology on the basis of a German design, leaving national shareholders in the Netherlands and UK to terminate their own design work by the middle of the decade.[35] Much of this coordination was attributable to Jack Parry (responsible for the Parry Paper many years earlier), still serving as a Urenco

[33] A. Lebrun, S.C. Kane, L. Bourva, S. Poirier, N.E. Loghin, D. Langlands, "Improved Verification Methods for Safeguards Verifications at Enrichment Plants," Proceedings of the First International Conference on Advancements in Nuclear Instrumentation, Measurement Methods and their Applications (Marseille, France: IEEE, June 7–10, 2009); Shephard, "*Process Attribute Monitoring Approach…*," 69.

[34] Prior to the mid-1980s, Troika centrifuge design efforts were largely undertaken separately by individual States. Although the original intent of the Troika had been to consolidate enrichment technology R&D and plant construction under a single "Prime Contractor" that would become known as Centec these responsibilities were conferred back to national shareholders after Urenco and Centec went through a restructuring process in October 1974. Collaboration on centrifuge design between all three Troika States began with work on the TC-12 centrifuge in the mid-1980s. See Kehoe, *The Enriching Troika,* 44–45; 71–73; 113–114; 133–140.

[35] Haskell to Gillmore, "Urenco Research and Development Presentation," TNA FCO 96/1402/29 (November 17, 1981), 3.

manager, and who was a strong advocate for a single Troika centrifuge.[36] By 1983, BNFL had entered into a design collaboration with Uranit, the West German Urenco shareholder.[37] The Netherlands joined this effort in 1985.[38] The resulting centrifuge design, known as the TC-12, was manufactured in all three Troika States, and used in all Troika plants.[39] TC-12 machines entered service in 1991.[40]

In concert with the Troika's newfound success with collaborative R&D through the 1980s, as manifested in the TC-12, another landmark development came: the flexible cascade. Until the introduction of flexible cascade technology to Urenco facilities in the early 1990s, the transparency assumption made by the HSP—that LFUAs using predominantly visual observation would be sufficient for verifying the absence of misuse, with NDA (using CHEMs) as a supplementary measure—was valid. Little over a half a decade later, this was no longer the case. With flexible cascade technology, an operator could change output enrichment levels without making any visible changes to cascade piping or external valves. Although some aspects of visual observation would remain effective with flexible cascades, such as the opportunity to verify the absence of undeclared material and feed/withdrawal points in cascade halls, verifying the absence of physical cascade modifications would become an ineffective measure. With flexible cascades, NDA needed to take on a more important role in LFUAs. However, given that the CHEM was the only NDA system available for header enrichment measurements at the time, it would have been entirely impractical to expand its role in LFUAs, as it already took several hours to perform a single measurement on

[36] Kehoe, *The Enriching Troika,* 119.
[37] Ibid., 113–114.
[38] Ibid., 133.
[39] Ibid., 134.
[40] Ibid., 140.

one cascade header. Performing a sufficient number of header pipe enrichment measurements to verify the absence of excess enrichment in a single LFUA would be impossible with contemporary technology. Meaningful verification of enrichment levels, therefore, would have to be performed via unattended monitoring systems with remote data transmission. A 2007 paper by IAEA safeguards staff reflects this logic, noting that flexible cascades "necessitated the need" for continuous header pipe enrichment monitoring, precipitating the creation of the CEMO system.[41] The paper further notes that "several technology holders," presumably all three Troika members, notified the IAEA of the implications of flexible cascade technology.[42] In addition, a 2006 IAEA safeguards symposium paper, also penned by IAEA safeguards staff, explicitly makes the link to use of continuous enrichment monitoring to flexible cascades, stating "[f]or flexible cascades, continuous monitoring to assure the absence of HEU should be performed where practicable. Where continuous monitoring of such cascades is not practicable, the frequency of LFUAs should be increased significantly."[43]

Development of the CEMO system began in 1990, and was carried out by the United Kingdom, under the auspices of the UK Support Programme to IAEA Safeguards, in collaboration with Euratom and the IAEA.[44] Like CHEM at the time, the system relied on low-resolution gamma spectroscopy using a sodium iodide detector to measure the intensity of the 186 keV gamma emission from ^{235}U. However, unlike CHEM, which used collimated XRF measurements to measure the gas density of UF_6 in piping, the CEMO relied on X-ray transmission via 20-50 keV

[41] Cooley et al., "Model Safeguards Approach…," 3.
[42] Ibid., 2.
[43] Bush et al., "Model safeguards approach for gas centrifuge enrichment plants," 623.
[44] T.W. Packer et al., "Review of the Current Status of CEMO Installed at Gas Centrifuge Enrichment Plants," IAEA-SM-351/169, Proceedings of the 1997 IAEA Safeguards Symposium (Vienna: International Atomic Energy Agency, 1997).

emissions from a ^{109}Cd source placed on the opposite side of the pipe from the NaI detector.[45] A considerable advantage of using a ^{109}Cd source over the CHEM's ^{57}Co source was that the half-life of ^{109}Cd is 463 days, 70% longer than ^{57}Co's 271-day half-life. Thus, source replacement for CEMO would need to be less frequent, although it has been reported that CEMO sources required replacement every 4-5 years,[46] or every 3-4 half-lives. The CEMO also adopted a simpler method for eliminating the effect of wall deposits, doing away with the CHEM's need for complicated custom collimators built to header specifications. Because development of the CEMO took place while flexible cascades were being installed, CEMO's developers could install the device on brand new piping, and directly measure the effect of wall deposits on CEMO measurements. Adam Shephard, in his 2016 doctoral dissertation, reports that four possible growth mechanisms exist for wall deposits: an initial deposit on virgin piping that forms as UF_6 begins flowing through the pipe, continuous air inleakage[47] during operation, abrupt air inleakage during operation, and "interim exposure to the atmosphere."[48] In essence, it can be deduced that CEMO was calibrated to subtract the effect of wall deposits from the gamma spectra that it measured, based on previous measurements on piping carrying known enrichments and wall deposit characteristics. Shephard reports that CEMO developers monitored wall deposit growth on a virgin product header as it entered use and reported that the system did not require re-calibration after formation of the initial deposit,[49] implying that continuous deposit growth during cascade operation was negligible at

[45] International Atomic Energy Agency, *Safeguards Techniques and Equipment: 2011 Edition*, International Nuclear Verification Series No. 1 (Rev. 2) (Vienna: International Atomic Energy Agency, 2011), 52.
[46] Cooley et al., "Model Safeguards Approach…," 3.
[47] Air inleakage causes deposit formation as water vapor in the air reacts with UF_6, forming UO_2F_2.
[48] Shephard, "*Process Attribute Monitoring Approach…*," 44.
[49] S.J. Baker et al., "The Introduction of a Continuous Enrichment Monitor for Safeguards Applications in Centrifuge Enrichment Plants," ESARDA (1995), cited in Shephard, "*Process Attribute Monitoring Approach…*," 42.

Capenhurst. CEMO testing began in 1991, seemingly in concurrence with Urenco's rollout of new enrichment technology, and CEMO was implemented at Capenhurst from 1995 through 2011, in a "go/no-go" regime, as measurements could only be taken with sufficient accuracy and precision to confirm the presence of LEU, and not to measure and report the actual enrichment of process material.[50] Over this time period, according to a UK Safeguards Support Programme report, two CEMO systems have been installed at Capenhurst,[51] although a Urenco paper states that CEMO systems were used to monitor 22 cascade product header pipes.[52]

The downside of CEMO's wall deposit correction technique was that if wall deposit growth did increase over time (particularly at a non-linear rate), then the system would need to be recalibrated on occasion. Furthermore, as reported by Shephard, CEMO was designed under the assumption that wall deposits were "minimal."[53] If the ratio of wall deposit signal to gas signal is too high, then the required measurement time to determine the contribution of the gas signal to a sufficiently precise degree may become impractically long. CEMO, like CHEM, was also prone to attenuation of photons by the pipe itself, and thus its effectiveness could be hampered by thicker header pipe walls, or the use materials with higher macroscopic photon cross sections (e.g. steel vs. aluminum). These vulnerabilities led to CEMO's failure to perform effectively when installed at Almelo. Urenco reports that CEMO was installed at Almelo in a field trial for one year in 1995-1996, but

[50] Roy J.G. Veldhof et al., "Overview of conducted field trials at URENCO: an operator perspective," Proceedings of the 2014 IAEA Safeguards Symposium (Vienna: International Atomic Energy Agency, 2014), 5.
[51] J.W.A. Tushingham, "UK Safeguards Support Programme: Report on Activities and Progress during the period 1 April 2010 to 31 March 2011," SRDP-PR31, UK Department of Energy & Climate Change (August 2011), 35.
[52] P.J. Friend, "URENCO Conference on GCEP Safeguards, held in December 2009," IAEA-CN-184/210, Proceedings of the 2010 IAEA Safeguards Symposium (Vienna: International Atomic Energy Agency, 2010), 4.
[53] Shephard, "*Process Attribute Monitoring Approach…*," 66.

this activity was terminated "due to problems with the equipment,"[54] presumably one of the issues discussed earlier in this paragraph.[55] CEMO was never implemented at Almelo following this field trial.

In addition, CEMO systems were never used at Gronau. This may have been partly due to the presence at Gronau of the same technological issues that hampered CEMO's utility at Almelo, but also because of political decisions taken by the German government and Euratom not to implement the system. WISE International, an anti-nuclear energy group, reported in June 1997 that the German government was using its influence in Euratom to pressure the IAEA (in its role as a regional safeguards authority, not as an inspectorate) to refrain from implementing additional safeguards measures at GCEPs, among other facilities.[56] In 1996, the IAEA was reportedly proposing CEMO implementation at all three Urenco facilities,[57] despite the Almelo field trial producing unsatisfactory results. This report states that Germany and Euratom were concerned about CEMO's false alarm rate, and that Germany had refused to install CEMOs at Gronau, even though CEMOs had already been delivered to the site.[58] Euratom Safeguards Head Wilhelm Gmelin corroborated this report in 1997, implying that CEMO's reliability prior to 1997 had been unsatisfactory, the system's user-friendliness could be improved, financing for the system's high cost needed to be guaranteed, and that implementation of CEMO needed to entail a maximum of 10–15 person-days of inspection (PDIs) per year for each GCEP in order for CEMO to be

[54] Veldhof et al., "Overview of conducted field trials at URENCO," 6.
[55] Shephard reports that experiments carried out in the late 1980s (pre-flexible cascade technology) showed that Almelo and Gronau featured lower gas pressures and higher deposit-to-gas ratios than equipment at Capenhurst. Shephard, "*Process Attribute Monitoring Approach…*," 63.
[56] WISE International, "Euratom against IAEA safeguards program," *Nuclear Monitor* 474 (June 13, 1997).
[57] Ibid.
[58] Ibid.

permissible.[59] In conclusion, pressure by Germany and Euratom succeeded against CEMO deployment at Gronau, and CEMO was never implemented at the site.

CEMO deployment, in conclusion, was extremely limited. While the system saw use at Capenhurst, it provided little utility at Almelo, and never saw use at Gronau. The limited deployment of CEMO stands in stark contrast with the rationale used by the IAEA to justify development of the system. As late as the second half of the 2000s, IAEA officials had argued publicly that the development of flexible cascade technology necessitated the development of continuous enrichment monitoring devices.[60] However, CEMO was only ever implemented at one of the three European facilities operated by Urenco, which had developed the flexible cascade. Despite the apparent necessity to deploy CEMO, in reality, CEMO was sparsely used.

By the early 2010s, CEMO was becoming technologically obsolete. Hardware and software for the system had become out of date,[61] and replacement of the ^{109}Cd sources every 4-5 years had proven to be "maintenance-intensive."[62] Although the UK Safeguards Support Programme undertook a study at the time on updating CEMO to improve its reliability and reduce maintenance costs, a decision was taken to cease the use of CEMO in 2011. Since then, no header pipe enrichment monitoring has been carried out for safeguards implementation purposes at any

[59] Gmelin, "Safeguards Policy and Technical Methodology from the Euratom Perspective," 5.
[60] See, for example, Cooley et al., "Model Safeguards Approach…,".
[61] K.D. Ianakiev et al., "Field Trial of LANL On-Line Advanced Enrichment Monitor for UF6 GCEP," Proceedings of the 53rd Annual Meeting of the Institute of Nuclear Materials Management (Orlando, FL, 2012), 2; Veldhof et al., "Overview of conducted field trials at URENCO," 6.
[62] Tushingham, "UK Safeguards Support Programme: Report on Activities and Progress during the period 1 April 2010 to 31 March 2011," 36.

Urenco-operated enrichment facility, or at the Areva-operated Georges Besse-II facility in Tricastin, France, which uses Troika enrichment technology.[63]

As CEMO reached the end of its life cycle, U.S. national laboratories worked to develop improved header pipe monitoring devices. The first device to be field-tested, the Advanced Enrichment Monitor (AEM) developed by Los Alamos National Laboratory, was never put into use by the safeguards inspectorates. Development of the AEM took place in 2008-2011, with the system clearly conceived using CEMO as a starting point, with the goal of mitigating CEMO's shortcomings. Like CEMO, the AEM used x-ray transmission measurements as a means for calculating gas pressure but used a powered x-ray tube instead of a sealed radiation source. To overcome accuracy issues due to the low gas pressure in cascade headers, AEM was designed to be installed on unit header piping, after the pump in the product (or tails) unit header that increases the gas pressure prior to cylinder filling, and before the pressure reduction station on unit feed headers. The AEM was field tested at Capenhurst from 2011 to 2013, during which it was confirmed that the system measured "with a high accuracy," but "some unexplained instabilities occurred."[64]

The AEM was never approved for safeguards use by either the IAEA or Euratom, perhaps due to these unexplained faults, or in part due to the development in the United States of a second header pipe monitoring technology, the On-line Enrichment Monitor (OLEM). While development of the

[63] OLEM field testing, by contrast, has taken place at Almelo, and OLEM demonstration was carried out at the Urenco USA GCEP constructed in the early 2010s in Eunice, New Mexico. See James R. Younkin and James R. Garner, "On-Line Enrichment Monitor Phase II Final Report: Techniques and Equipment for Safeguards at Gas Centrifuge Enrichment Plants," ORNL/LTR-2017/108 (Oak Ridge National Laboratory, February 2017).
[64] Veldhof et al., "Overview of conducted field trials at URENCO," 6.

AEM predated the IAEA decision to phase out CEMO, development of the OLEM was made upon the request of the IAEA as it contemplated whether to proceed with a CEMO update. The IAEA made an initial request for the development of a new header pipe enrichment monitor in early 2010,[65] which the U.S. safeguards support program accepted. Oak Ridge National Laboratory was chosen to carry out this task and led the development pipeline for what would become OLEM.

OLEM bears similarities to the AEM. Like the AEM, it was designed for unit header measurements, and like the AEM and CEMO, it uses a sodium iodide detector for measuring the 186 keV gamma line from ^{235}U. Unlike previous systems, however, the OLEM relies on direct measurements of UF_6 gas pressure and temperature, entirely doing away with the need for radiation sources, and their associated inconvenience. Two options were conceived for OLEM pressure measurements: use of the operator's existing pressure measurement equipment, which would be housed in a tamper-proof enclosure with a signal splitter to allow the operator to continue taking pressure measurements, or a dedicated pressure sensor installed by the inspectorate.[66] Furthermore, a new wall deposit correction technique for OLEM was explored that took advantage of pressure transients in headers attributable to the connection of empty cylinders in withdrawal stations. If the pressure and temperature of gas in the header are known, and the gas enrichment is assumed to be constant during this transient, counts attributable to background and the wall deposit can be subtracted from the measured spectrum, on the basis of the essentially linear relationship between UF_6 pressure (and ^{235}U atomic density) and count rate in the 186 keV region of interest in the

[65] Interview with U.S. safeguards expert, November 2, 2016.
[66] L. Eric Smith, Alain R. Lebrun and Rocco Labella, "Potential Roles for Unattended Safeguards Instrumentation at Centrifuge Enrichment Plants," *Journal of Nuclear Materials Management* 42, no. 1 (2013): 45.

OLEM detector.[67] In sum, OLEM's new pressure measurement and wall deposit correction method, although potentially dependent on the trustworthiness of operator equipment or the invasive installation of a pressure measurement device inside an operator's piping, offered a far more reliable and simpler approach than previous header pipe monitoring systems.

Development of the OLEM system ran in concurrence with the negotiations that led to the agreed Joint Comprehensive Plan of Action (JCPOA) between the permanent members of the United Nations Security Council, Germany, the European Commission, and Iran. OLEM field-testing began at Almelo in June 2014,[68] approximately six months after the Joint Plan of Action (JPOA) had been agreed between the same parties as a confidence building measure as part of negotiations of the JCPOA. Results from OLEM field tests were "promising,"[69] which likely influenced the inclusion of language in the July 2015 JCPOA committing Iran to "permit the use of on-line enrichment measurement."[70] In January 2016, the IAEA reported that it had installed OLEM technology at Iran's Natanz Fuel Enrichment Plant (FEP) as part of JCPOA implementation.[71] All public information available to date indicates, however, that OLEM has only been deployed for safeguards use at the Natanz FEP. The Natanz FEP is the only GCEP worldwide where continuous header enrichment monitoring technology is used for under comprehensive (INFCIRC/153-type) IAEA safeguards.

[67] L. Eric Smith et al., "Modeling and Analysis Methods for an On-Line Enrichment Monitor," *Journal of Nuclear Materials Management* 44, no. 3 (2016), 31.
[68] Veldhof et al., "Overview of conducted field trials at URENCO," 6.
[69] Ibid.
[70] "Joint Comprehensive Plan of Action" (Vienna, July 14, 2015), Annex 1, para. N.67.1.
[71] Vincent Fournier and Miklos Gaspar, "New IAEA Uranium Enrichment Monitor to Verify Iran's Commitments under JCPOA," (International Atomic Energy Agency, January 16, 2016).

Continuous header pipe monitoring has also been applied under IAEA safeguards at a Chinese GCEP located in Hanzhong, Shaanxi Province, under the Chinese Voluntary Offer Agreement.[72] The vast majority of China's uranium enrichment capacity, estimated in 2015 to be approximately 4500 tSWU/a and growing, is not subject to international safeguards, with the exception being Phases I and II of the Hanzhong GCEP, which together constitute approximately 500 tSWU/a of separative capacity,[73] far less than a typical modern commercial GCEP. Both Phases I and II of the Hanzhong plant, constructed in the mid- to late 1990s, use Russian centrifuge technology, and are subject to an agreement made between the Russian and Chinese governments, and the IAEA under a dedicated effort known as the Tripartite Enrichment Project (TEP). As the TEP carried out its work, it was acknowledged that some of the assumptions made during formulation of the HSP approach would not apply at Hanzhong. In particular, unannounced cascade inspections would not be practicable if carried out separately from routine inspections, given the travel necessities that existed at the time. Furthermore, Russian-type centrifuges and cascade equipment were reported to be "designed for a much greater degree of operational flexibility than other plants,"[74] implying that excess enrichment could be far more easily accomplished than at facilities considered by the HSP. Given these considerations, a separate safeguards approach for Hanzhong Phases I and II was developed by the TEP.

Given the flexibility of the Russian equipment, it is unsurprising that continuous enrichment monitoring was considered for use at Hanzhong, especially since CEMO had recently gone into

[72] "Agreement of 20 September 1988 between the People's Republic of China and the International Atomic Energy Agency for the Application of Safeguards in China," INFCIRC/369 (Vienna: International Atomic Energy Agency, October 1989).
[73] Hui Zhang, *China's Uranium Enrichment Capacity: Rapid Expansion to Meet Commercial Needs*, Belfer Center for Science and International Affairs (Harvard University, August 2015), 7.
[74] A. Panasyuk et al., "Tripartite Enrichment Project…," 1.

routine safeguards use at Capenhurst. The TEP, however, found that CEMO would be ineffective at the facility, which featured steel cascade header piping with higher photon attenuation properties than Capenhurst's cascade headers. In addition, the plant's flexible design meant that UF_6 product streams could easily be routed around an enrichment monitor installed on a cascade product header.[75] Thus, when the TEP concluded, participants agreed to explore developing a new continuous enrichment monitor for Hanzhong.[76]

The continuous enrichment monitor developed for the Hanzhong facility was developed by the China Institute of Atomic Energy.[77] Like CEMO, AEM, and OLEM, it uses a sodium iodide detector. To counteract the cascade piping flexibility problem, it is mounted "at the product pipe of [sic.] cascade hall,"[78] effectively the unit header pipe, in Western terms. The Chinese device, like OLEM, relies on pressure measurements from operator equipment, avoiding the need for x-ray sources, but overcomes the wall deposit problem with a different method. Unlike all other header pipe monitors, the Chinese enrichment monitor, is not directly mounted on the piping itself, but instead is installed in parallel with the header pipe, with valves installed at each end that can direct the flow of UF_6 through the monitor. The monitor collects UF_6 in a 15-liter Marinelli beaker, from which radiation measurements are taken.[79] This setup provides a stronger signal than a direct header pipe measurement, although this means that measurements are strictly not carried out in real time. Although the material used for this vessel is unspecified, it may be presumed that it can be removed for cleaning and/or be replaced as deposits build up, as necessary. This enrichment

[75] Ibid., 3–4.
[76] Ibid., 4.
[77] Xue-Sheng Lyu et al., "Development of an On-line Uranium Enrichment Monitor," Proceedings of the 2014 IAEA Safeguards Symposium (Vienna: International Atomic Energy Agency, 2014), 2.
[78] Ibid., 5.
[79] Ibid., 3.

monitor has reportedly been in service at Hanzhong for "several years."[80] Nevertheless, Hanzhong Phases I and II represent a small fraction of the overall enrichment capacity installed in China today, the latter of which is expected to grow further as China's efforts to develop its civil nuclear energy continue.[81]

To conclude, although header pipe monitoring is explicitly cited as a safeguards measure for verifying the absence of misuse in the HSP approach, and although several devices have been developed since the HSP approach was negotiated, implementation of header pipe monitoring has not been widespread, both in the past and today.

2. Environmental Sampling

As discussed in Chapter 2, environmental sampling technology (ES) became available for safeguards use in the early 1990s, motivated by the discovery of Iraq's secret nuclear weapons program in the aftermath of the first Gulf War and subsequent efforts through Programme 93+2 to investigate how to improve the IAEA's ability to discover undeclared nuclear activities. ES constituted a powerful tool in this regard, as it allowed for the detection of trace amounts of nuclear material released through an undeclared activity in samples of vegetation, soil, and water in its vicinity. Within buildings, processes involving nuclear material also result in the deposition of particles containing nuclear material on surfaces, which can be picked up by inspectors with cotton swipes, and analyzed for isotopic content. Swipe sampling inside GCEP process areas can thus be

[80] Ibid., 6.
[81] Zhang, *China's Uranium Enrichment Capacity*, 6.

used to detect whether HEU has been present in the facility, and if undeclared HEU production has taken place.

Following a successful series of field trials, which ran between September 1993 and March 1995, the IAEA Board of Governors approved the implementation of ES as a safeguards measure under INFCIRC/153-type safeguards from 1996 onwards.[82] At the outset, ES was prioritized for swipe sampling at enrichment plants, as well as at facilities containing hot cells.[83] Furthermore, from the beginning of ES implementation, swipe samples were collected inside cascade halls during LFUA activities. As the deposition of uranium-bearing particles is more likely in the proximity of openings in process piping, cascade header pipe connections, process gas sampling areas, and feed/withdrawal stations were identified as locations for swipe sampling. Cascade maintenance carts were also deemed to be useful.[84] Baseline samples were first established at facilities before routine swipe sampling took place.

While environmental swipe sampling provides inspectorates with an additional capability to detect the past production of HEU (or excess uranium enrichment), the technique does not allow for rapid detection of these activities. Environmental samples, once collected, must undergo laboratory analysis. All swipe samples collected by IAEA inspectors from enrichment facilities are shipped to the IAEA's Environmental Sample Laboratory (ESL), located in Seibersdorf, Austria, for screening. Because the ESL does not have the capacity to analyze all the samples it receives, some

[82] J. Cooley, "Environmental Sampling," Proceedings of the Technical Workshop on Safeguards, Verification Technologies, and Other Related Experience (Vienna: International Atomic Energy Agency, 1998), 1. http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/30/050/30050977.pdf.
[83] Ibid.
[84] Ibid., 3.

samples are then shipped to members of the IAEA's Network of Analytical Laboratories (NWAL). NWAL laboratories, which are located in IAEA Member States, perform sample analyses on behalf of the IAEA. In order to qualify as an NWAL member, a laboratory must go through a rigorous qualification process to ensure that it analyzes samples with sufficient accuracy and precision, as prescribed in the IAEA's International Target Values.[85] Environmental samples shipped to NWAL members are anonymized so that their origin is unknown to the laboratory, and the IAEA also ships "quality control samples" to NWAL laboratories to continuously assess the accuracy of NWAL results.[86] This process takes substantial amounts of time. In 2006, IAEA safeguards staff reported that the typical delay between sampling and result evaluation was three to four months,[87] in excess of the 1–3 month timeliness goal for misuse detection established by the HSP. Although the IAEA made efforts to reduce the turnaround time for environmental samples, potentially allowing for a delay of three weeks in the late 2000s[88] and as little as fifteen days by 2016,[89] this amount of time still far exceeds the amount of time that it may take for a modern commercial GCEP to produce a weapons-usable quantity of HEU, and for diversion of the material to occur. This observation will be reinforced in the following chapter.

Thus, while the advent of ES added a powerful new tool to GCEP safeguards, allowing inspectorates to attain a very high probability of detection for excess enrichment and HEU

[85] International Atomic Energy Agency. *International Target Values 2010 for Measurement Uncertainties in Safeguarding Nuclear Materials*. STR-368 (Vienna, November 2010).
[86] Aabha Dixit, "Swipe check: collecting and analysing environmental samples," *IAEA Bulletin* 57, no. 2 (June 2016), 22.
[87] Bush et al., "Model safeguards approach for gas centrifuge enrichment plants," 6.
[88] Cooley et al., "Model Safeguards Approach…," 6.
[89] Andrew Green and Aabha Dixit, "IAEA Safeguards Labs More Efficient and Accurate Thanks to Recent Upgrades" (International Atomic Energy Agency, June 10, 2016), https://www.iaea.org/newscenter/news/iaea-safeguards-labs-more-efficient-and-accurate-thanks-to-recent-upgrades.

production, the time associated with ES analysis detracts from its ability to detect misuse in a timely manner.

3. The Additional Protocol

The IAEA's drafting of the Model Additional Protocol (published as INFCIRC/540) followed from the work of Programme 93+2, which had identified both safeguards strengthening measures (like location-specific environmental sampling) that could be conducted under the authority of existing comprehensive safeguards agreements, and measures that would require additional agreement between States and the IAEA. The main objective of these measures, collectively, was to bolster the IAEA's ability to detect undeclared nuclear fuel cycle activities in States under safeguards. After the Model Additional Protocol (AP) was approved by the Board of Governors in May 1997, States were given the option to conclude an AP with the IAEA on the basis of the text of INFCIRC/540. At present, APs are implemented in all non-nuclear weapon states (NNWS) with GCEPs, with the exception of Brazil. Meanwhile, all NPT nuclear weapon states (NWS) have also concluded an AP with the IAEA. The content of the NWS APs, however, often differs from that of the Model AP: while the U.S. AP is nearly identical to INFCIRC/540 and implements nearly all of its provisions, other NWS APs are far more selective in their implementation of Model AP measures.[90] Although the AP contains provisions that enhance the IAEA's ability to detect undeclared activities at GCEPs, however, the HSP approach remains the basis for on-site activities

[90] Eva C. Uribe et al., "A Comparison of the Additional Protocols of the Five Nuclear Weapon States and the Ensuing Safeguards Benefits to International Nonproliferation Efforts," LA-UR-09-04012, Proceedings of the 50th Annual Meeting of the Institute of Nuclear Materials Management (Tuscon, AZ, 2009).

at GCEPs, including verification of the absence of facility misuse. This section discusses the effect of the AP's provisions on on-site inspection activities at GCEPs.

The AP provision that is most directly relevant to on-site inspection activities at GCEPs concerns additional access rights for IAEA inspectors that exceed those in INFCIRC/153, known as complementary access (CA). Different types of CA exist, which can broadly be grouped into three categories, each with a different purpose: to verify the absence of undeclared nuclear material and activities, to verify the additional information about nuclear fuel cycle-related activities that States are required to provide under the AP (known as the 'expanded declaration'), and to verify the decommissioned status of a site.[91] The first type of CA, when performed at any place on a declared nuclear site (thus named 'on-site CA' in this discussion), can be carried out with a notice period of two hours when sought in conjunction scheduled on-site inspection activities (i.e. design information verification, ad-hoc, or routine inspections), and with 24 hour notice in all other instances.[92] This gives the IAEA the right to access, in theory, any location at a given GCEP in an AP State, although the AP also requires arrangements to be made for 'managed access' to reduce the risk of spreading commercially or proliferation-sensitive information, and in the interests of safety and security.[93] Furthermore, CA was not conceived as a tool for systematically verifying information in the expanded declaration or for drawing material accountancy conclusions.[94] Instead, CAs are to be used essentially as 'spot checks' that build the credibility of an observed absence of undeclared material and activities. In this way, CA enhances the IAEA's ability to

[91] "Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency for the Application of Safeguards," INFCIRC/540 (Vienna: International Atomic Energy Agency, September 1997), art. 4.a.
[92] Ibid., arts. 4.b, 5.a.(i).
[93] Ibid., art. 7.
[94] Ibid., art. 4.a.

verify the absence of undeclared enrichment capacity or material at a given GCEP. For example, CA gives the IAEA power to send inspectors into a building on a GCEP site declared to be for non-nuclear purposes (e.g. an office building)[95] and verify that it does not contain undeclared enrichment equipment or undeclared nuclear material. The utility of CA is greatly enhanced by the IAEA's increased use since the mid 1990s of open source information, IT-based information analysis tools, and the State-level safeguards framework, which together can be used to target CAs with greater effectiveness. This type of CA, however, does little to assist the IAEA in detecting GCEP misuse using declared enrichment equipment, as inspectors already had the right to access cascade areas with two hours' notice under the HSP's LFUA provision. Thus, while on-site CA at sites provides substantial benefits in the realm of verifying the absence of undeclared capacity and material at a GCEP, particularly in the presence of information giving the IAEA reason to search a given location, on-site CA provides fewer benefits with respect to the detection of excess enrichment or HEU production.

CA can also be applied outside declared sites. Among these applications, CA can be used to resolve questions or inconsistencies concerning information provided under the AP's expanded declaration, which obligates safeguards reporting authorities to provide information on the fabrication of centrifuges and rotor tubes, including the scale of operations at each manufacturing location.[96] This power gave the IAEA newfound authority to access centrifuge and rotor tube manufacturing workshops, which it did not have previously, as nuclear material subject to safeguards is typically not present at these locations. As a result, in AP States, the IAEA is able to

[95] Article 2.a.iii of INFCIRC/540 requires the provision of a site map, along with descriptions of each building, including their contents.
[96] Ibid., art. 2.a.(iv); Annex I.(i).

verify that centrifuge production is commensurate with a State's civil enrichment program. While GCEP is being built or expanded, centrifuge manufacturing rates should be consistent with its physical size and planned capacity, and while GCEPs are operating, centrifuge production should proceed at a far lower rate, perhaps only producing centrifuges at the rate of machine failure, or at rates justified by centrifuge exports. This type of CA generates confidence as to absence of undeclared enrichment capacity within a given State, as the IAEA is able to check whether centrifuge production rates are reasonably bounded by declared GCEP capacity, as well as exports of centrifuges and centrifuge components to other States. However, CAs at manufacturing plants, like on-site CAs, do not significantly improve safeguards authorities' ability to detect excess enrichment or HEU production using declared equipment already installed at a GCEP.

In the first decade of AP implementation, CA activities at Troika facilities mainly took place at centrifuge manufacturing plants.[97] However, in the case of Troika facilities, and in many other GCEPs, centrifuge assembly workshops are located on the same site as the enrichment facility. For such facilities, justification for an on-site CA (with shorter notice, and no requirement to resolve a question or inconsistency) may be valid. Nevertheless, regardless of which type of CA is used to justify a visit to a centrifuge manufacturing operation, the conclusion stands that CA does little to verify the absence of facility misuse to produce higher-than-declared enrichments.

[97] Peter Friend, "Urenco's Views on International Safeguards Inspection," Proceedings of the 8th International Conference on Facility Operations – Safeguards Interface (Portland, OR, 2008), 3.

4. Cascade Access in Brazil

Amidst efforts to strengthen international safeguards from the 1990s onwards, which registered a minimal improvement to misuse verification capabilities, contentious negotiations reemerged over the issue of cascade access. These discussions, however, concerned cascade access at the Resende GCEP in Brazil, a non-HSP and non-AP State. Centrifuge development in Brazil commenced in secret in 1979, when the Brazilian navy embarked on a program known as Project Cyclone. Research progressed slowly at first, with only a handful of engineers. By 1987, a 48-centrifuge test cascade had been set up, which was expanded to 500 machines in 1991,[98] shortly after the Brazilian military acknowledged the existence of the program in 1990.[99] All of this activity, however, ostensibly undertaken to provide future Brazilian nuclear submarines with enriched fuel,[100] took place prior to Brazil joining the NPT. Prior to acceding to the NPT in 1998, Brazil concluded a safeguards agreement with the IAEA, Argentina, and the recently constituted Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC). International safeguards activities at the Resende plant, which went into limited operation in 2006,[101] are governed by this agreement, known as the Quadripartite Agreement.

Discussions on IAEA safeguards measures to be applied at Resende, which is operated by Brazil's state-owned civil nuclear operator, reached an impasse in early 2004, after what was presumably a design information verification visit, prior to the introduction of nuclear material to the facility.

[98] Erico Guizzo, "How Brazil Spun the Atom," *IEEE Spectrum* 43, no. 3 (March 2006): 50–56.
[99] Daphne Morrison, "Brazil's Nuclear Ambitions, Past and Present," (Nuclear Threat Initiative, September 1, 2006), http://nti.org/4250A.
[100] Ibid.
[101] Ibid.

Upon entering the cascade area at Resende, IAEA inspectors found that panels and coverings had been constructed to shroud centrifuge casings and enrichment equipment from view.[102] At other safeguarded GCEPs, centrifuge casings and header pipes were visible to IAEA inspectors, and could be observed during LFUAs to verify the absence of any modifications. The IAEA was unsatisfied with this arrangement, as shielding essentially all enrichment equipment from view would eliminate the value of cascade access. Meanwhile, Brazilian officials were adamant that the centrifuge casings needed to be shielded from view, as the Brazilian navy-designed centrifuges reportedly featured an unusual proprietary design that used two electromagnetic bearings to levitate each centrifuge rotor,[103] allowing it to spin almost entirely without friction.

The dispute between the IAEA and Brazil over centrifuge shrouding continued until late 2004, when the two parties came to a compromise. According to third-party reports, the IAEA and Brazil agreed to allow the use of panels at Resende to obscure centrifuge casings from view albeit at a reduced size.[104] IAEA inspectors are permitted to view "the top of the centrifuges" with a camera,[105] which allows inspectors to verify that header connections have not been modified, while not being able to see any the centrifuge casings considered proprietary by Brazil. A 2007 IAEA report describes a procedure for verifying header configurations in cascade halls with panels, almost certainly referring to those in Brazilian facilities:

> "During an LFUA, cascade positions are randomly selected for design verification. With the inspector present but out of direct view of the cascade, the operator opens the relevant

[102] Peter Slevin, "Brazil Shielding Uranium Facility; Nation Seeks to Keep its Proprietary Data from U.N. Inspectors," *The Washington Post*, April 4, 2004, A01.
[103] Squassoni and Fite, "Brazil as Litmus Test…;" Guizzo, "How Brazil Spun the Atom."
[104] Guizzo, "How Brazil Spun the Atom."
[105] Carlos Feu Alvim, "Alternative to the Additional Protocol of the Nuclear Safeguards Agreement with the IAEA," *Economy & Energy* IX, no. 52 (October-November 2005).

> panel and takes a photograph of the upper centrifuge header pipe connections and of the cascade floor between the centrifuges from overhead. The pictures are authenticated by having the operator include a unique object in the photograph (e.g. the inspector's passport). The inspector then compares the photographs with baseline pictures that were taken in a similar manner."[106]

According to the same report, inspectors may also perform gamma and neutron NDA measurements on the panels to verify the absence of concealed UF_6 cylinders.[107] In addition, Brazil and the IAEA reportedly agreed to additional containment and surveillance measures at UF_6 feed and withdrawal points.[108]

Although Brazil and the IAEA were able to agree to a mutually acceptable solution regarding inspector access in cascade areas, this incident demonstrates that cascade access for inspectors and the protection of commercially sensitive and proliferation-sensitive enrichment technology has continued to be a delicate issue, long since HSP participants resolved the issue among themselves in the early 1980s.

5. An Improved Model Approach for GCEP Safeguards: Addressing Undeclared Feed

In the mid-2000s, the IAEA finally revisited the question of how to verify the absence of undeclared feed in GCEPs through the development of a new model safeguards approach, as part of efforts to further strengthen the safeguards system after conclusion of the Model AP. By this point, the potential presence of undeclared material at an enrichment plant was no longer a debatable point, as it was during the HSP. The IAEA's experience with Iraq had shown NPT States

[106] Cooley et al., "Model Safeguards Approach…," 4.
[107] Ibid., 3.
[108] Squassoni and Fite, "Brazil as Litmus Test…."

Parties that had accepted safeguards could not necessarily be trusted or expected to make a complete declaration of all nuclear material in their possession. Meanwhile, Germany (now a unified State) and Japan, which both bitterly opposed any explicit references to undeclared material during the HSP, had concluded Additional Protocols with the IAEA, giving the IAEA far greater power and purpose for verifying the absence of undeclared material and activities within their borders. Over two decades since the HSP finished its work, it was finally time to address the issue of undeclared feed.

In contrast with the primarily technology holder-driven dialog that drove GCEP safeguards negotiations in the 1970s and 1980s, development of the improved model GCEP safeguards approach was led by the IAEA. By the mid-2000s, the IAEA had substantial experience implementing safeguards in a variety of commercial GCEPs, empowering it with the knowledge it needed to argue its case for where safeguards measures could be strengthened. First, in 2004, the IAEA acknowledged a need to update the model GCEP safeguards approach that had served as a basis for plant-specific safeguards approaches (each taking into account the characteristics of individual GCEPs) since the end of the HSP.[109] The IAEA subsequently drafted and reviewed a new approach internally, before hosting a five-day technical meeting in April 2005 on "Techniques for IAEA Verification of Enrichment Activities" that included experts in enrichment technology safeguards technology, safeguards policy, GCEP operators, and IAEA safeguards staff.[110] Feedback from this meeting was incorporated into the new model approach, which was presented to the IAEA Director General's Standing Advisory Group on Safeguards Implementation (SAGSI)

[109] Bush et al., "Model safeguards approach for gas centrifuge enrichment plants," 617.
[110] Ibid.

in December 2005.[111] After further review, taking SAGSI's input into consideration, the new approach was presented and approved by the IAEA Board of Governors in June 2006.[112] Although archival documents on Member State engagement with the IAEA on this issue have not yet been released, available evidence indicates that discussions over the improved model approach were not particularly controversial.

Drafters of the IAEA's improved model GCEP safeguards approach recognized the fact that no single safeguards approach could be applied to all GCEPs in operation,[113] likely due to differences between facilities including enrichment technology characteristics, separative capacities, and plant layouts. Thus, the aim of the improved approach (similarly to the HSP-approved approach) was not to prescribe a single regime of measures to be applied at all safeguarded commercial GCEPs, but to provide a range of measures that could be applied as necessary. Nevertheless, safeguards at GCEPs would still share three overall objectives, which were the timely detection of the diversion of declared material, misuse to enrich material in excess of declared levels, and misuse to produce undeclared material (using undeclared feed) at or below declared product enrichment levels.[114] With implementation of the improved model approach, the IAEA finally explicitly addressed undeclared feed as a GCEP safeguards issue. This provision is the most significant aspect of the new approach.

In the improved model approach, the undeclared feed scenario is addressed, as described in Chapter 2, using the combination of high-frequency electronic mailbox declarations paired with

[111] Ibid., 618.
[112] Ibid.
[113] Cooley et al., "Model Safeguards Approach…," 7.
[114] Ibid., 2.

Short-Notice Random Inspections (SNRIs) to feed and withdrawal (F/W) stations. The purpose of the SNRIs is to verify that the identities of cylinders reported to be in F/W stations are as declared. U.S. safeguards experts proposed that SNRIs could be carried out in conjunction with LFUAs, which at the time were reportedly taking place approximately 6-10 times per year at safeguarded GCEPs—within the range for 1000 tSWU/a facilities recommended by the HSP.[115] The same experts also argued that this concept would not require additional inspection effort, as data from SNRIs could be used in place of material balance data gathered during IIVs.[116] This protocol was field-tested at Gronau in 2007.[117] Although Urenco reported the test to have been a success,[118] the company also had reservations over whether verifying the absence of undeclared feed was worthwhile, arguing that operation of a completely clandestine facility would be more likely than production of undeclared LEU at a declared plant, followed by further clandestine enrichment of the material. In 2008, Urenco's Safeguards and Security Head wrote,

> "The IAEA currently seems very excited about being able to detect undeclared enrichment production - using undeclared uranium. But Urenco can't understand why a proliferator would ever want to do that. If I wanted to produce HEU for nuclear weapons, why should I make secret LEU in a plant under the spotlight of IAEA, and then further enrich this in a completely separate, but secret enrichment plant? That doesn't make sense at all, since this is far too complicated, and there would be two opportunities for the IAEA to discover this. It would be far simpler to just enrich secret supplies of uranium in a secret plant. There would be less chance of being found out."[119]

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[115] Brian D. Boyer, David M. Gordon and Jae Jo, "Use of Mailbox Approach, Video Surveillance, and Short Notice Random Inspections to Enhance Detection of Undeclared LEU Production at Gas Centrifuge Enrichment Plants," Proceedings of the 47th Annual Meeting of the Institute of Nuclear Materials Management (Nashville, TN, 2006), 7.
[116] Ibid., 1.
[117] P.J. Friend, "Field Trial of Mailbox Concept at a Urenco Enrichment Plant," Proceedings of the 49th Annual Meeting of the Institute of Nuclear Materials Management (Nashville, TN, 2008), 6.
[118] Veldhof et al., "Overview of conducted field trials at URENCO," 3.
[119] Friend, "Urenco's Views on International Safeguards Inspection," 6.

Despite this complaint, the new inspection concept was implemented in 2009 at all three European Urenco GCEPs. While Urenco has not voiced outright opposition to the mailbox-SNRI system, it has criticized some of its ramifications. First, while Urenco did acknowledge that "the IAEA reduced inspections," presumably IIVs, as a result of implementing SNRIs, Urenco pointed out that Euratom did not change its inspection regime on account of SNRI data, thus leaving overall inspection effort unchanged.[120] Second, the electronic mailbox system provided a potential security vulnerability to Urenco IT networks. In one instance reported by Urenco, an IAEA inspector connected a virus-infected USB stick to a computer connected to the mailbox system, which was discovered and neutralized by Urenco's IT security software.[121] Despite these issues, however, implementation of the mailbox-SNRI system appears to have continued.

Although the most significant difference between the improved model approach and the original HSP approach concerns the treatment of undeclared feed, the new approach also endorsed other safeguards measures and concepts, including environmental sampling (which had already been implemented GCEPs for the past decade), the use of operator equipment whenever possible, and a defense-in-depth approach to use of safeguards measures.[122] Little was changed in the new approach, however, regarding the role of LFUA for detecting over-enrichment of material, even though a proposal was made to increase the frequency of LFUAs at flexible plants where CEMO was not installed.[123] It is unclear whether this specific suggestion was adopted, as well as the degree by which LFUAs would be increased although it was mentioned with reference to the defense-in-

[120] Veldhof et al., "Overview of conducted field trials at URENCO," 3.
[121] Ibid.
[122] Bush et al., "Model safeguards approach for gas centrifuge enrichment plants," 617–618; Cooley et al., "Model Safeguards Approach…," 7.
[123] Bush et al., "Model safeguards approach for gas centrifuge enrichment plants," 622–623.

depth concept.[124] In sum, however, the improved model approach largely focused on the undeclared feed problem, while acknowledging implementation of incremental improvements to means for detecting material diversion and over-enrichment.

Conclusions

From this chapter, a handful of conclusions can be drawn about the evolution of GCEP safeguards implementation from the HSP to today. First, it should be apparent that with few exceptions (e.g. the use of SNRIs in the place of IIVs by the IAEA), the implementation of material accountancy at GCEPs, to date,[125] has changed little since the end of the HSP. Efforts to improve GCEP safeguards effectiveness have focused on the two misuse objectives: enrichment of material beyond declared levels, and undeclared feed. Second, it is arguable that the LFUA frequency agreed by the HSP, even at the time, did not afford inspectorates a particularly high probability of discovering an abrupt episode of HEU production using existing equipment, offering a 10–28% chance of detection if a ten-day misuse episode were to occur once in a given year at a 1000 tSWU/a GCEP. Nevertheless, these odds may have been high enough to provide a substantial deterrent to misuse at such a facility. Third, considerable effort has been devoted to improving the safeguards inspectorates' ability to detect GCEP misuse, including the development of various types of continuous header monitoring technologies, and the implementation of environmental sampling, complementary access, and the mailbox/SNRI system. While continuous header pipe

[124] Ibid.

[125] The U.S. Support Program to IAEA Safeguards has been developing an Unattended Cylinder Verification Station (UCVS) in recent years for automating the process of weighing and assaying UF_6 cylinders, with the goal of improving the efficiency of GCEP material accountancy. This system, however, has not yet been deployed by safeguards inspectorates. The UCVS will be discussed in the following chapter.

monitoring was driven in part by advances in enrichment technology, these advances were driven in large part by efforts to strengthen the IAEA's ability to detect undeclared nuclear activities and material that began with Programme 93+2. The fourth observation, however, is that none of these misuse verification measures have significantly improved the IAEA's ability to detect the over-enrichment of UF_6 using declared enrichment equipment, either by design or by implementation. Header enrichment monitoring, no less continuous header enrichment monitoring, has been sparsely used. Environmental sampling does not provide timely results. Meanwhile, complementary access and the mailbox/SNRI system more effectively address undeclared enrichment capacity and undeclared material, respectively. Thus, as commercial GCEPs have become more flexible and grown in capacity, the ability of inspectorates to detect misuse at these facilities has not kept pace, leading to a gap between the current needs for safeguards effectiveness, and the capabilities of international safeguards inspectorates. The following chapter provides technical motivation for why this is the case, before proposing possible paths forward.

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Chapter 8 – Considering Misuse Detection at Modern Commercial Gas Centrifuge Enrichment Plants

This chapter draws its content from M.E. Walker and R.J. Goldston, "Timely Verification at Large-Scale Gas Centrifuge Enrichment Plants," Science and Global Security 25, No. 2 (2017): 59–79.

1. Introduction

Today, global uranium enrichment demand for civil nuclear energy production is almost entirely dominated by the gas centrifuge process. At the present day, a typical commercial gas centrifuge enrichment plant (GCEP) site houses at least 4,000 tSWU/a of enrichment capacity. This is four times more than the SWU capacity for which the HSP's chosen LFUA frequency—4–12 cascade area inspections per year—was deemed appropriate, given the technology and inspection measures approved at the time. The previous chapter established that in the years since the HSP, despite concerted efforts by inspectorates and their Member States to improve the ability of safeguards inspectorates to detect GCEP misuse, very little has changed regarding the most critical aspect of GCEP safeguards: detecting the enrichment of material to levels higher than declared, and in particular, the production of highly enriched uranium (HEU). In short, while GCEP capacities and their associated potential for rapid HEU production have grown substantially, enhancements to verification capabilities for detecting this activity, in general, have been minimal. This observation yields the question of whether a gap has emerged between safeguards verification needs and means at GCEPs today. If a gap exists, a question follows: what can be done to ensure that GCEP safeguards continue to be effective and efficient?

The previous chapter focused on the evolution of verification means that have been applied for GCEP safeguards. This chapter focuses on the question of what is *needed* for robust safeguards verification, in particular verifying the absence of higher-than-declared material enrichment values, at current GCEPs. To make an assessment on verification needs, a hypothetical HEU production scenario is modeled, using a Python script, at a 'reference' enrichment facility featuring an assumed unit and cascade layout, to estimate the possible durations of misuse episodes producing a significant quantity (SQ) of HEU, as well as associated HEU production rates. This approach, while not faithful to reality (as will be explained later), produces far more realistic results than completely idealized calculations that estimate 'breakout' times by dividing the requisite SWU capacity for producing an amount of material by the nominal capacity of a facility, or a portion thereof.[1]

It is important to account for factors other than a nominal facility capacity. The physical layout of a given GCEP as well as the size, number, and arrangement of production units and cascades, play a significant role in determining practical misuse scenarios. Two cascades in separate units, for

[1] A completely idealized calculation, as described in the main text, produces rather alarming results, assuming a facility capacity of 4000 tSWU/a. The production of one significant quantity (SQ) of 90%-enriched weapons-grade HEU starting from 8.9 t of naturally enriched uranium hexafluoride (UF_6) requires approximately 5,400 kilograms of separative work (kgSWU), or 5.4 tSWU, assuming a product enrichment of 90% and a tails enrichment of 0.30%. Starting from 0.87 t of 5%-enriched UF_6, only 1.2 tSWU are required, with a tails enrichment of 0.71%. A single 4000 tSWU/a plant, capable of fueling about thirty 1 GW(e) nuclear reactors, could then, in this idealized calculation, produce 2.0 SQ of 90%-enriched uranium per day continuously from natural UF_6 feedstock. Alternatively, using an on-hand supply of 5%-enriched UF_6, ideally it could produce 9.1 SQ of weapons-grade HEU per day before consuming its stock of feed material. One month's prior production of 5%-enriched uranium would be 69t of UF_6, so 80 SQ could be produced in 8.8 days, using this supply. A similar calculation for a 500 tSWU/year production unit yields 10 SQ in 8.8 days. Either of these highly idealized scenarios would present a very serious challenge for timely detection and deterrence of the misuse of nuclear technology for the manufacture of nuclear explosive devices, the fundamental goal of IAEA safeguards.

example, generally cannot be connected to each other with ease. Effort is also an important factor: some misuse scenarios may require an impractical amount of manpower and time in order to be executed and are thus less attractive than other scenarios that require much less time and labor. There is also the question of how long it takes for a cascade, or a system of cascades, to equilibrate after reconfiguration, or after the feed assay is changed. Thus, in order to establish where present safeguards measures and approaches could be strengthened, while taking into account the above issues, it is useful to consider a basic plumbing diagram for a reference large-scale gas centrifuge enrichment plant. Following from this concept, a simple discrete time model was created for estimating cascade behavior during, hypothetical GCEP misuse scenarios, both through transient phases and at steady state. Results of the simulations performed for this chapter yield the conclusion that the expanded use of unattended monitoring systems (UMS) with remote transmission capabilities, both in the existing application of header pipe monitoring and in new applications, will be vital to the continued effectiveness and efficiency of GCEP safeguards.

Five sections follow in this chapter. Section 2 considers the plumbing diagram of a reference GCEP to determine practical HEU production scenarios. In this section, estimates are presented for the time required for a new reconfigured system, with a new feed assay, to come to equilibrium, based on the discrete time model. Section 3 assesses the potential signatures of these misuse scenarios. Section 4 outlines a potential toolbox of UMS technologies that could be drawn from to provide timely detection and therefore deterrence against the scenarios defined in Section 2 and related scenarios. Section 5 briefly examines possibilities for responding to UMS data indicating possible misuse, and Section 6 summarizes the chapter and makes recommendations.

2. Sample Scenarios

This section examines how misuse scenarios might be implemented at a reference gas centrifuge enrichment plant. Sample scenarios only consist of 'abrupt diversion' cases where a GCEP is used to produce large quantities of uranium enriched in excess of 90% (by isotopic fraction) as quickly as possible without detection.[2] Since direct access to weapons-usable material is provided through such scenarios, they place the greatest stress on the question of timeliness, more so than the diversion of natural, depleted or low-enriched uranium, or the excess production of LEU.

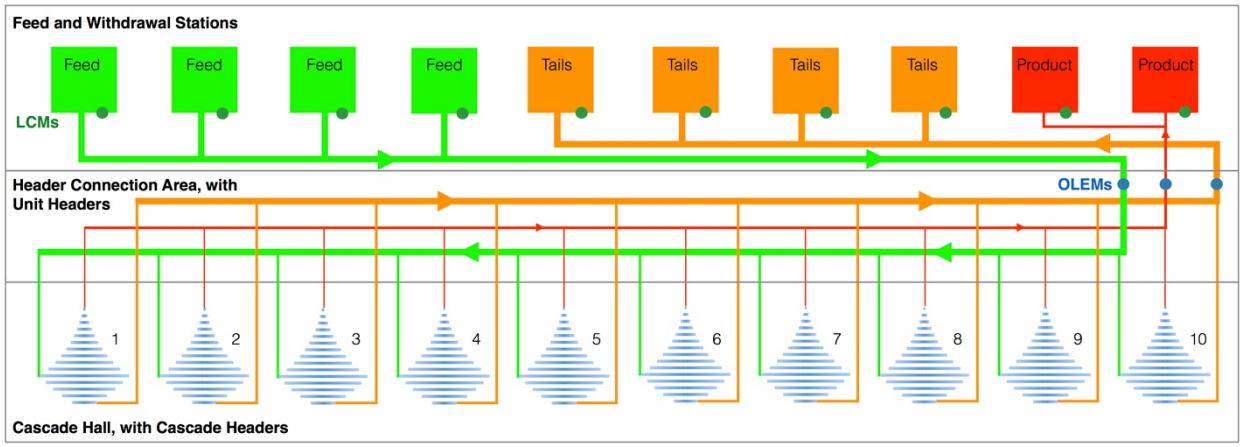

Figure 8-1: Simplified "plumbing diagram" for a single 500 tSWU unit of a reference gas centrifuge enrichment plant. The number and position of feed and withdrawal stations is arbitrary. LCM (Load Cell Monitoring) stations and OLEMs (On-Line Enrichment Monitors) are discussed in Section 3.

In a 2013 article, Smith, Lebrun and Labella[3] introduce a "reference" gas centrifuge enrichment plant, with nominal 4000 tSWU/year capacity. The reference plant is made up of eight "units," of

[2] International Atomic Energy Agency, *IAEA Safeguards Glossary, 2001 Edition*, International Nuclear Verification Series No. 3 (Vienna: International Atomic Energy Agency, 2002), 21.
[3] L. Eric Smith, Alain R. Lebrun and Rocco Labella, "Potential Roles for Unattended Safeguards Instrumentation at Centrifuge Enrichment Plants," *Journal of Nuclear Materials Management* 42, no. 1 (2013): 38–58.

which one is illustrated in Figure 8-1, each consisting of ten cascades. Each unit has a header connection area, where cascade headers are joined to form unit headers, as well as a bank of feed and withdrawal (F/W) stations for uranium hexafluoride (UF_6) gas. Each unit has a nominal 500 tSWU/year enrichment capacity, while each cascade has a nominal 50 tSWU/year capacity. For round numbers it Is assumed that each centrifuge has a nominal 50 kgSWU/year capacity, and thus each cascade is made up of 1000 centrifuges. A further assumption, again for round numbers, is that these centrifuges operate with gain at each stage of $\gamma = \alpha\beta = 1.2^2$, where $\alpha = R'/R$ and $\beta = R/R''$, and relative isotopic abundance R is defined as:

$$R(N) = \frac{N}{1 - N} \tag{8.1}$$

in which N is the atomic fraction of ^{235}U relative to the total uranium atomic abundance at a given point in a cascade. By convention, R and N without single prime ($'$) or double prime ($''$) markings represent material fed into a given stage. A single prime marking following R or N designates upflow from a stage, and a double prime marking indicates relative abundance and enrichment values for downflow from a stage. Note that all enrichment values given in this chapter are by atomic (molar) fraction, and not by weight.

A scenario where with $\alpha = \beta = 1.2$ allows a cascade to enrich material from 0.72% ^{235}U to 5.11% in eleven stages under ideal operating conditions. Assuming four stages of these same centrifuges on the stripping side, the tails are produced with an enrichment value of 0.29%. In order to estimate the equilibration time of the cascades, it is assumed, once again for round numbers, that each centrifuge contains 10g of uranium, or about 14.8g of UF_6. Material in pipes between centrifuges

is neglected, as it can be inferred from previous studies that the amount of material in piping is small (<~10%) relative to the amount of material in centrifuges.[4]

There are a number of potential approaches for misusing an enrichment plant to produce weapons-usable material.[5] In the sample scenarios here, it is assumed that the operator chooses to maintain the integrity of the individual cascades (not moving centrifuges between cascades) but does place the cascades into a new series-parallel configuration. For simplicity and scalability, and to avoid long interconnections, it is further assumed that the operator maintains the integrity of the individual units, neither moving cascades between units, nor making connections between units. Enriched UF_6 produced in one unit, however may be transferred in cylinders to other units.

An operator planning to misuse an enrichment facility would encounter the problem that the higher cascades in a linked "cascade of cascades," composed of cascades designed for enrichment to 5%, are not ideally shaped. Ideal, optimally efficient cascades designed for higher enrichments have a blunter shape (i.e. have relatively more centrifuges in higher stages) than do cascades for lower enrichments. In this scenario, the operator might re-plumb centrifuges within a cascade into the ideal blunter configuration to maximize efficiency. This could, however, entail a significant amount of physical work in the centrifuge hall, which would require labor, time, materials and

[4] Patrick J. Migliorini, "*Modeling and Simulation of Gas Centrifuge Cascades for Enhancing the Efficiency of IAEA Safeguards*," (PhD diss., University of Virginia, 2013), and J. Ely et al., "On-Line Enrichment Monitor (OLEM): Supporting Safeguards at Enrichment Facilities," E-poster presented at the 2014 IAEA Safeguards Symposium, (Vienna: International Atomic Energy Agency, 2014). Given the cascade piping characteristics, and dimensions and operating parameters for the centrifuges specified in Migliorini, along with the operating pressure for cascade piping given in Ely et al., it becomes apparent that the ratio of material in piping to material in centrifuges is quite small.

[5] Alexander Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapons Proliferation," *Science and Global Security* 16 (2008): 1–25.

supplies, and considerable advance preparation, resulting in enhanced risk of early detection. A quicker and perhaps less detectable alternative might be to "prune" centrifuges from the cascades, which involves removing centrifuges from service in order to form the ideal shape, at the cost of reducing the separative work available. This could also require significant labor, depending on the operational properties of the cascades. Approximately two thousand centrifuges would be need to be removed from service out of the ten thousand assumed to compose a unit. It should be recognized that remotely operable valves and/or otherwise flexible cascades and centrifuges could simplify these scenarios.

A very quick and simple option, however, would be to leave the cascades in their original configuration, and feed them at their nominal mass flow rate, but at higher enrichment, while leaving all cut values unchanged. This modestly reduces the separative capacity of the cascades relative to their nominal capacity (at an ideal state), due to mixing of flows with differing enrichment, but, perhaps surprisingly, increases their overall enrichment gain. Conservation of total uranium atoms and atoms of ^{235}U in a single centrifuge or cascade stage can easily be shown to require:

$$\theta = \frac{(1 + \alpha R)(\beta - 1)}{(1 + R)(\gamma - 1)} \tag{8.2}$$

where θ is the "cut" or fraction of the feed atoms going into the product, and R is the ratio of ^{235}U to ^{238}U atoms in the feed to the centrifuge or stage. For $\alpha = \beta$, equation 8.2 reduces to the well-known formula for the ideal cut,[6]

$$\theta = \frac{1 + \alpha R}{(\alpha + 1)(1 + R)} \tag{8.3}$$

Equation 8.3, incidentally, shows that the ideal cut grows with R, explaining the blunter shape at higher enrichment. On the other hand, with a non-ideal cut, θ, defined by optimization for lower enrichment, and with increased R, equation 8.2 shows the necessary relationship between α and β. It is assumed that the stage separation factor $\gamma = \alpha\beta = R'/R''$ is, or can be arranged to be, approximately independent of θ and R, ignoring any other non-ideal effects that may be associated with operating at higher enrichment. Since α and β are both modestly above unity, the $(\beta - 1)$ term provides the dominant variation on the right-hand side of equation 8.2, so β falls below α as θ falls below the ideal value. This is what happens when a cascade configured for a lower enrichment level is fed with material of higher enrichment (it is well known,[7] and simple to see physically, that as the limit $\theta = 0$ is approached, β must approach unity and so α must approach $\alpha\beta$). With higher α and lower β, a cascade will produce more highly enriched product. This makes it possible to traverse from LEU suitable for use in power reactors to material of enrichment in excess of 90% in only two cascade groups, as shown in Table 8-1, rather than the three groups typically assumed

[6] Karl Cohen, *The Theory of Isotope Separation as Applied to the Large-scale Production of U-235* (New York: McGraw-Hill, 1951), 6.
[7] B. Brigoli, "Cascade Theory," in *Uranium Enrichment*, ed. Stelio Villani, Topics in Applied Physics, Vol. 35 (New York: Springer-Verlag, 1979), 21.

for ideal cascades.[8] This two-step non-ideal approach can achieve 90% enrichment using cascades each with 11 enriching stages (as assumed here), but capable of product enrichment of only 4.6% and $\alpha = \beta = 1.19$. With $\alpha = \beta = 1.2$, as in this case, the minimum enrichment of LEU feedstock required to achieve 90% enrichment is 3.7%.

Table 8-1: Sets of Cascades in Abrupt Diversion Scenario

	Feed Enrichment	Product Enrichment	Tails Enrichment	tSWU/year
Original	0.72%	5.11%	0.29%	50
Mid-group	5.11%	34.0%	2.29%	49.5
Top	34.0%	94.1%	28.1%	28.4

The ratio of feed to product flow in these cascades is uniformly 11.2. Thus, a single ten-cascade unit could be reconfigured to have nine mid-group cascades feeding directly into a single top cascade, leaving some capacity to spare in the top cascade. To implement this scenario, as shown in figure 2, only two modifications would be needed, solely in the header connection area.

1) The unit feed header would need to be disconnected from the cascade #10 feed header, but could otherwise remain unmodified, connected to all of the other cascade feed headers and to all of the feed stations.

2) The unit product header would need to be broken between cascades #9 and #10, and connected to the #10 cascade feed header.

[8] For fixed $R_{product}/R_{feed} = 5.93$ in each set of cascades, four sets of cascades are required to achieve 90% enrichment by the stages: 0.72% to 4.1%, 4.1% to 20.3%, 20.3% to 60.3% and 60.3% to 90%. To achieve 90% enrichment in 3 stages requires $R_{product}/R_{feed} = 10.75$, which is appropriate for producing 7.2% enriched U from natural uranium.

The cascade #10 product header would feed unmodified into the remainder of the unit product header and so on to the product withdrawal station. Remarkably, no other changes would be required.

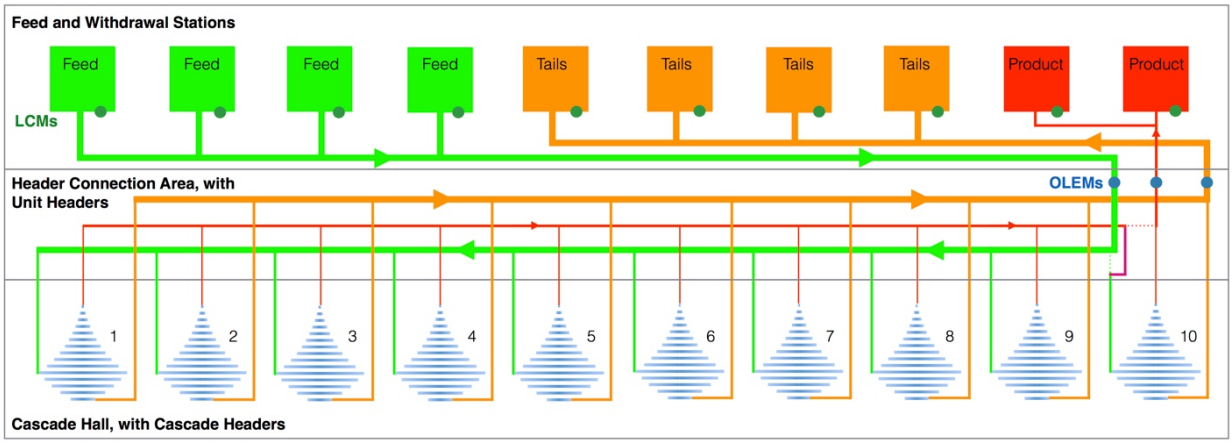

Figure 8-2: Simplified plumbing diagram for a single 500 tSWU unit of a reference gas centrifuge enrichment plant, modified in the vicinity above cascade #10 to produce HEU. New piping in magenta; eliminated piping in red dots. Compare with Figure 8-1.

A question arises as to what the operator would do with the tails from the mid-group and top cascades. Ten stripping stages (rather than the installed four) would be required for the tails to emerge from a given cascade at the same enrichment level as a lower cascade's feed. It is assumed that an operator trying to execute an abrupt diversion of weapons-grade HEU would judge that the addition of these stages would be too time-consuming, so instead the tails from the higher cascades would be captured and stored for recycling. The fastest approach, requiring the least modification of the system, would be simply to leave the existing tails cascade headers *exactly as they are*, continuing to feed the unit tails header, itself unmodified, and capture the tails from the mid-group and top cascade together. This approach is somewhat inefficient, since it mixes flows of different enrichment. It is, however, expeditious, optimally simple, and yields LEU of only a modestly lower

enrichment than the material that is fed into the unit. This material can therefore be used to supplement the feed to the mid-group, which is discussed in further detail later in this section.

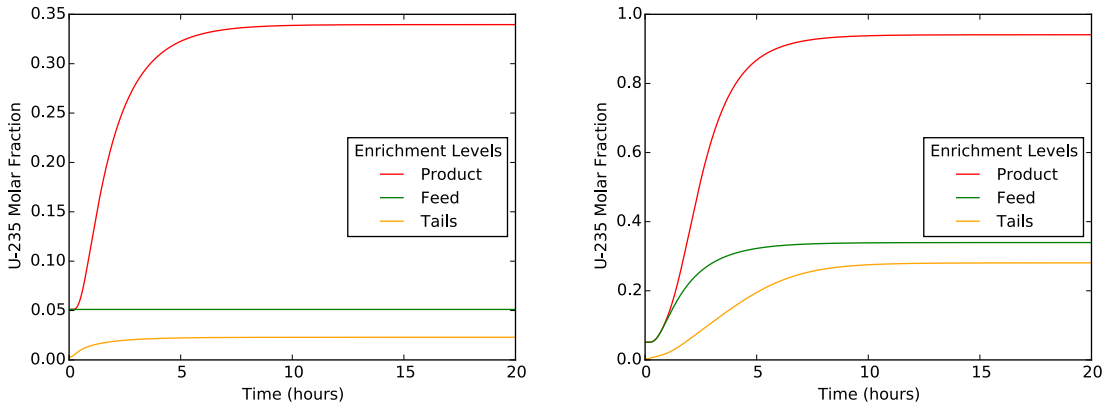

Figure 8-3: Time evolution of product, feed and tails ^{235}U concentrations of the mid-group cascades (left) and the top cascade (right).

Once the cascades are reconfigured, the next key step is to bring them to equilibrium at their new operating point. Figure 8-3 shows calculations of the time evolution of their enrichment levels (assuming that tails are not recycled in this case). An explicit time-stepping model, coded in Python, was developed for carrying out these calculations. The model calculates both flows and material assay in a cascade, given a set of user-specified characteristics, including cascade shape and cuts, centrifuge hold-up and operating parameters. In this case, the model assumes that total molar flow through each centrifuge is constant, but with time-varying enrichment. This obviates the need for new hydrodynamic modeling, since no mass flows are changing significantly. Thus, all of the isotope-summed centrifuge and cascade flows are retained. Given the molar flow rates at each time step, the model calculates the amount of material (in moles) and enrichment level in each stage during each time step.

During each time step, the flow of material out of each stage is calculated first. The amount of material (in moles) that remains in each stage during a time step, m_{ret}, is given by:

$$m_{ret} = m_{s,t} - (L_{s,t}{}' + L_{s,t}{}'')\Delta t \tag{8.4}$$

where $L_{s,t}'$ and $L_{s,t}''$ are respectively the molar flow rates for material moving to the stages above and below during the timestep, $m_{s,t}$ is the stage holdup, and Δt is the length of the timestep. Ideal stage flow rates were assumed for the original cascade enrichment, unconstrained by the granularity of individual centrifuges.

Next, the enrichment of the material retained in the stage, N_{ret}, can be calculated, by:

$$N_{ret} = \frac{N_{s,t} m_{s,t} - (L_{s,t}{}' N_{s,t}{}' + L_{s,t}{}'' N_{s,t}{}'')\Delta t}{m_{ret}} \tag{8.5}$$

where $N_{s,t}$ is the average molar enrichment of material in a stage at the beginning of the time step, assuming immediate and full mixing, and $N_{s,t}'$ and $N_{s,t}''$ are respectively the enrichments of material moving to the stages above and below during the timestep, such that

$$N_{s,t}{}' = \frac{\sqrt{\gamma} R_{s,t}}{1 + \sqrt{\gamma} R_{s,t}} \tag{8.6}$$

and

$$N_{s,t}'' = \frac{R_{s,t}}{\sqrt{\gamma} + R_{s,t}} \tag{8.7}$$

where

$$R_{s,t} = \frac{N_{s,t}}{1 - N_{s,t}} \tag{8.8}$$

$R_{s,t}$ represents the average molar ratio of ^{235}U to ^{238}U *inside the stage* (as opposed to in the feed) of a given stage, s, at time t. Note that γ is assumed to be constant, since the model does not allow for any change in the total molar flows, and higher-order changes to γ associated with enrichment level are ignored.

The mass and enrichment of material in each stage at the end of a time step is calculated, by also including the inflow of material,

$$m_{s,t+\Delta t} = (L_{s-1,t}' + L_{s+1,t}'' + F_{ext})\Delta t + m_{ret} \tag{8.9}$$

$$N_{s,t+\Delta t} = \frac{(L_{s-1,t}' N_{s-1,t}' + L_{s+1,t}'' N_{s+1,t}'' + F_{ext} N_{ext})\Delta t + N_{ret} m_{ret}}{m_{s,t+\Delta t}} \tag{8.10}$$

where the subscripts *s-1* and *s+1* denote the stages immediately below and above stage *s*, respectively, F_{ext} is the mass flow rate of feed material at the feed stage (F_{ext} is zero at all other stages), and N_{ext} is the feed enrichment.

In a situation where a cascade shape is sharper than ideal for the enrichment at which it is operating (e.g., the case at hand where the enrichment is higher than the design value) a smaller flow of enriched material is sent from a given stage to stages above because the cut is too low, and a greater flow of depleted material is sent to stages below, relative to the ideal case. The result is that the enrichment of the material in the centrifuges trends upwards over time relative to the enrichment of their feed. When equilibrium is reached, the values of α and β, calculated from the enrichment of the feed, product and tails of each stage, are found to be in excellent agreement with equation 8.2 – even though α and β relative to the average enrichment of material inside the centrifuges remain, by construction, at 1.2.

Equilibration takes place quite rapidly with the assumed inventory of UF_6 per centrifuge. As shown in Figure 8-3, the product enrichment of the top cascade crosses 90% after approximately 6 hours and equilibrates to approximately 94% enrichment in 12 hours. Operating parameters common to Original, mid-group and top cascades are given in Table 8-2. A step time of 8 seconds was used for this simulation.

Table 8-2: Operating parameters for a 50 tSWU reference cascade producing LEU

Stage	Initial stage feed enrichment, $N_{s,0}$	Stage Cut, θ_s	Stage flow rate, L_s (g UF_6/s)	Stage holdup, m_s (g UF_6)
-4	0.35%	0.4549	5.89	615.73
-3	0.42%	0.4549	10.80	1129.48
-2	0.50%	0.4550	14.90	1558.46
-1	0.60%	0.4551	18.33	1917.01
0	0.72%	0.4552	21.20	2217.12
1	0.86%	0.4553	17.14	1792.89
2	1.03%	0.4555	13.76	1439.11
3	1.24%	0.4557	10.94	1144.04
4	1.48%	0.4559	8.58	897.85
5	1.77%	0.4562	6.62	692.36
6	2.12%	0.4565	4.98	520.72
7	2.53%	0.4568	3.61	377.23
8	3.02%	0.4573	2.46	257.10
9	3.61%	0.4578	1.49	156.33
10	4.30%	0.4585	0.68	71.57

Before presenting further results, it is important to note that these estimates only take into account losses in separative capacity due to the mixing of flows containing different enrichments. These calculations do not account for higher-order effects that may become significant at higher enrichments, and thus production figures given in this chapter should be taken to be approximate, but still illustrative of the time scale on which GCEP misuse can occur, and of timeliness needs for safeguards.

Two limiting-case misuse scenarios are now outlined. The first is a scenario in which pre-existing stocks of LEU (in this case, featuring 5%-enriched material) are fed into a plant with all units modified in the simple manner described above, until the LEU stocks run out. The second is a

scenario in which some units are left unmodified and continue to produce LEU for feeding into two modified units. Both scenarios take advantage of tails recycling in the modified units. While the first scenario allows for faster production of weapons-grade material per unit of plant capacity, as separative work is only applied to enriching LEU to weapons-grade uranium (and not to enriching natural uranium to LEU), production can only continue as long as stocks of LEU last. The second scenario, on the other hand, allows for continuous production of weapons-grade material, but at a slower rate, as the plant is effectively enriching natural uranium to weapons-grade, instead of LEU to weapons-grade, as in the first situation. For both types of misuse, it should be noted that the top cascade will be slightly starved of material, as the feed-product ratio of each cascade is 11.2, but the top cascade only has 9 cascades feeding it. Thus, the top cascade will produce HEU at 9/11.2=80.4% of its capacity. The product flow rate for an ideal 50 tSWU/a cascade enriching natural uranium to 5.11%-enriched material is about 77 mol/day. Running at an 80% capacity factor, the top cascade will produce about 62 mol/day, which is roughly equivalent to 0.5 SQ/day at 90% enrichment. The number of moles in an SQ of HEU, however, is inversely proportional to enrichment, as the SQ is defined as 25 kg of ^{235}U in an undefined amount of HEU. Thus, at product enrichments higher than 90%, production rates in terms of SQ will be slightly higher, and vice versa for enrichments lower than 90%. Additionally, it is well known that operating a countercurrent centrifuge at a feed rate below the optimum level increases the machine's gain.[9] Thus, SQ production rates and product enrichments may in reality be slightly higher than reported here, working to offset neglected higher-order effects.

[9] Migliorini, "*Modeling and Simulation of Gas Centrifuge Cascades…*," 40.

For the fastest production scenario, a fully reconfigured (nominal) 4000 tSWU/year plant, with one month's plant production of 5.11%-enriched U on hand, can theoretically produce about 11 SQ of weapons-grade material in about 3 days, including equilibration time (but not re-configuration time), on the basis of the model presented here. The tails from this process, including those collected during equilibration of the first cycle, could be recycled through the unit in two further cycles, theoretically allowing for a total production of approximately 29 SQ of weapons-grade material in about one week. Both the amounts that can be produced, and the production time, vary linearly with respect to the pre-existing stockpile, making this a very important factor. The maximum production rate, however, remains theoretically at 4.4 SQ/day for the whole plant. A 500 tSWU/year unit, considered as a stand-alone facility starting from one month's production of LEU produced solely by that unit, could theoretically produce 3.6 SQ in 7.3 days.

In a steady misuse scenario, 2 units can be reconfigured in the 8-unit reference facility as described above, with tails recycled from the modified units into their own feeds along with the feed from the 6 unmodified units. Doing this would naturally reduce the enrichment of feed going into the mid-group, as well as the enrichment of material produced by the top cascade. Because the enrichment of the combined tails of the mid-group and top cascades is only slightly depleted relative to the mid-group feed, and because the original scenario had some margin above 90% enrichment, however, it is possible to still produce weapons-grade material when recycling tails material. (The precise result is 89.1% enrichment, but this does not take into account the reduced feed to the top cascades and their resulting higher gains.) In this case 31 SQ per month (i.e. ~1 SQ/day) could nominally be produced at a continuous rate, for as long as natural UF_6 is supplied to the plant.

The production rates in these two scenarios correspond to approximately factor of 2 reductions from the highly idealized calculations presented in footnote 1 (which took into account neither practical reconfiguration options nor equilibration times) both in total product from a given stored quantity of LEU and in production rate. Nonetheless, these more realistic results still constitute a significant challenge for timely verification, especially given the minimal piping reconfiguration effort required in both scenarios. Assuming that the unit reconfiguration described in this chapter can be carried out nearly instantaneously, an equilibration time of twelve hours prior to and after misuse, and an HEU production rate on the order of 1 SQ/day, it could be reasonable to assume that an abrupt HEU production episode, producing at least 1 SQ of material, could take place in as little as two days. Such a short 'breakout' time challenges the utility of the Limited Frequency Unannounced Access (LFUA) model for detecting higher-than-declared material enrichment: using equation 2.11, an LFUA frequency of 4–12 inspections/year only has a 2–6% chance of detecting a single 2-day HEU production episode within a given year. Although routine physical inventory verification (PIV) and interim inventory verification (IIV) may detect the diversion of material used in the misuse scenario, these activities only take place on the order of every month. Thus, once diversion of LEU has been detected, it is quite possible that sufficient time will have elapsed to allow for the removal of the resulting HEU to a clandestine location for conversion and fabrication into a weapons component, making a proliferator's construction of a nuclear weapon a *fait accompli* by that point.

It is important to recognize that these calculations represent limiting cases. A potential proliferator, for example, could choose to modify fewer than 8 units, and produce the same amount of HEU

from stored LEU over a longer period of time. Alternatively, a proliferator could choose not to recycle the tails from the modified units in either scenario. There are even mixed scenarios where the proliferator desires to produce the maximum material over a given period of time, say one month, so starts by processing existing LEU in modified units but also produces additional LEU during this time. Evidently there is a balance that could be struck between amount of modification effort (and associated risk of detection) and rate of production of material before detection.

3. Potential Signatures

Before discussing the utility of safeguards measures in detecting the misuse of large GCEPs in the following section, it is worthwhile assessing the signatures that could be detectable during a misuse scenario, indicating off-normal operation at a facility.

Clearly, in both misuse scenarios, enrichment levels in the feed, product, and tails unit headers would be higher than in normal operation. In a modified unit, LEU would be present in the feed and tails unit headers, and HEU would be present in the product unit header. Feed and tails cylinders (e.g., 48Y-type) containing LEU, as well as cylinders containing HEU, would be present in process areas. It may be possible for a proliferator to feed standard LEU product cylinders with HEU (at the required 8% of the standard capacity, since it would be fed by a single cascade operating at 9/11.2 flow rate) in withdrawal cells without exceeding criticality limits.[10] Traces of

[10] The criticality safe dimension for an infinite 90%-enriched ^{235}U slab is 3.8 cm. This is about an order of magnitude smaller than the 36.83 cm inner radius of a 30B product cylinder. Thus, a 0.8 cm-thick layer of 90%-enriched UF_6 desublimated on the inner walls of a 30B cylinder would also be criticality safe. This corresponds to about 190 kg of UF6, which is about 8% of a 30B cylinder's 2277 kg maximum fill weight for LEU up to 5%-enriched material. The product cylinder fill rate for the misuse scenarios described in this paper is about 8% of that under normal operation. See U.S. Program for Technical Assistance to IAEA

HEU, which would be detectable by environmental sampling, would materialize in process areas. The presence of LEU at feed and HEU at withdrawal stations would result in higher levels of neutron radiation per unit mass of UF_6 in those areas, due to higher levels of ^{234}U in process material, as alpha particles emitted by ^{234}U induce an (α,n) reaction in fluorine contained in UF_6[11]. The time rate of change of this neutron emission could not be masked by operating with smaller masses of total UF_6. Piping reconfigurations (as described in Section 2) would also be necessary either in the header connection area, or the cascade hall. This could be accomplished via the installation of piping between sample ports already installed in the process area, or via the construction of new ports or connection points. If the latter option involves making openings in existing pipework that has carried UF_6, the release of some UF_6, and the products of UF_6 hydrolysis, uranyl fluoride (UO_2F_2) and hydrogen fluoride (HF), would be likely. Takeoff points closer to the centrifuges than the feed/withdrawal areas may also be installed, possibly in the header connection area or in cascade halls. Visible evidence of reconfigured pipework may or may not exist, depending on the location of the activity.

Header flow rates would be abnormal: in particular, the flow rate in the product unit header outside the header connection area would be dramatically reduced to 8% of normal. The flow rate in the unit's feed header would nominally be 10% below normal (as only 9 of 10 cascades would be fed from that header). The tails unit header would carry a slightly lower-than-normal flow rate, as although it would be receiving the tails of 10 cascades, the tails output of the top cascade would

Safeguards, *Nuclear Material Safeguards for Uranium Enrichment Plants: Part 3–Uranium Enrichment Plant Description and Material Control and Accountability Procedures*, ISPO-347/R8 Part 3 (Oak Ridge National Laboratory, 2007), 5.62.

[11] Mark M. Pickrell et al., "Detection of Illicit HEU (^{235}U) in a Fuel Cycle Enrichment Plant," Proceedings of the 47th Annual Meeting of the Institute of Nuclear Materials Management (Nashville, TN, 2006).

reflect that it is slightly starved of feed. The fill rates of withdrawal cells, and the emptying rates of feed cells would also reflect these flow rates, particularly if undeclared feed and takeoff points exist.

Inconsistencies could emerge in the handling of UF_6 cylinders within the plant. Tails recycling would involve the movement of containers from withdrawal cells into feed cells, which should not happen at an enrichment plant under normal operation. In the fast production scenario, LEU stocks are used, which might necessitate the movement of full product cylinders from storage into a process area, which would be a sign of abnormal activity. A signature of a continuous operation scenario would be the frequent movement of full UF_6 cylinders between units. These cylinders might be full product cylinders, although feed cells may be designed only to accept larger feed/tails cylinders, thus necessitating the transfer of UF_6 from product containers into larger cylinders, perhaps using product blending equipment, modified as necessary. Regardless of cylinder type, LEU in these cylinders, in addition, would not be available for verification, as it would have been fed into a modified unit.

Additionally, in the event that product cylinders are used to feed a modified cascade instead of feed/tails cylinders, the changeout frequency of cylinders in feed cells would be higher than usual. Operator load cell data in feed cells, if available to an inspectorate, would reflect this.

Finally, inconsistencies would emerge in plant operations at a higher level. During a covert misuse scenario, a proliferator might physically conceal UF_6 cylinders (product, feed, and tails) containing off-normal enrichments. If safeguards authorities believe a plant is operating at the time of misuse,

then the absence of material in product and tails cylinders commensurate with the plant's declared production would constitute cause for further investigation. In a continuous scenario, LEU production and shipments would necessarily cease or be significantly reduced, as LEU product from unmodified units would need to be fed into modified units. By contrast, in a fast production scenario, unmodified units would still be able to produce product LEU as normal, which the facility would be able ship out, albeit at lower rates that would be inconsistent with normal operation. Nevertheless, prior to a fast production scenario, an operator may enrich LEU to higher levels (e.g. 5%) than would be produced under a normal operational scenario, in which a larger range of LEU enrichments might be produced. If material balance records were falsified in any of these scenarios, clear discrepancies would be apparent between these figures and observable material during IIV or PIV activities.

4. Toolbox of Verification Technologies

Section 2 established that the LFUA model, as it is practiced currently, is challenged by the scale of modern gas centrifuge enrichment plants. Increased inspectorate use of unattended monitoring systems (UMS) with remote transmission capabilities may mitigate this situation. This section outlines a toolbox of potential unattended verification technologies that could be implemented to provide timely detection of HEU production signatures listed in Section 3, and thus deterrence against the scenarios defined in Section 2, and related scenarios.

As discussed in the previous chapter, discussions on the use of unattended systems at GCEPs stretch began in the early 1990s with the Continuous Enrichment Monitor (CEMO), although

deployment of the system and its technological successors has never been widespread. In 2013, Smith, Lebrun and Labella[3] proposed three technologies for unattended safeguards at their large "reference" enrichment plant: the then-nascent On-Line Enrichment Monitor (OLEM), Load Cell Monitoring (LCM), and the Unattended Cylinder Verification Station (UCVS). These technologies are briefly described below, along with their relevance to the sample scenario.

OLEM: On-Line Enrichment Monitoring systems,[12] as described in Chapter 7, are non-intrusively attached to *unit* headers, as shown in Figure 8-1. They may be attached to the product, feed and tails headers of each unit, so the reference GCEP discussed in Section 2 could be equipped with 24 such systems. By use of photon emission measurements, with calibration to remove the effects of pipe deposits, these systems can determine to a few percent accuracy the density of ^{235}U in the gas flowing through the unit header. By use of temperature measurements on the outside of the header pipe and inspectorate- or operator-installed pressure sensors, the density of UF_6 gas can be inferred, allowing an accurate assessment of the enrichment level of the gas in the unit header pipe. This technology has been qualified for application, and as discussed in Chapter 7, has been deployed in Iran.[13] OLEM systems could also provide co-benefits to GCEP operators, as enrichment measurements from these devices could be used for process control.[14]

[12] L. Eric Smith et al., "Modeling and Analysis Methods for an On-Line Enrichment Monitor," *Journal of Nuclear Materials Management* 44, no. 3 (2016): 27–44.
[13] James Ely et al., "Enrichment Measurement with the On-Line Enrichment Monitor (OLEM)," Proceedings of the 57th Annual Meeting of the Institute of Nuclear Materials Management (Atlanta, GA, 2016).
[14] Roy J.G. Veldhof et al., "Overview of conducted field trials at URENCO: an operator perspective," Proceedings of the 2014 IAEA Safeguards Symposium (Vienna: International Atomic Energy Agency, 2014).

LCM: Load Cell Monitoring consists of time-dependent measurement of the mass of UF_6 cylinders in all F/W stations attached to each of the unit headers, as shown in Figure 8-1. This measurement would be carried out by the facility operator and it would be challenging to verify the authenticity of this measurement independently. The requirements for a technology to allow reliable sharing of information from load cell monitors are under development.[15] Load cell data may be considered commercially sensitive by operators, and thus establishing procedures for acquiring and handling this information may be challenging. In addition, as Smith, Labrun and Labella point out, modern GCEPs typically feature over 100 F/W stations, each of which would need to be configured for data sharing with inspectorates.[16] Undertaking this task could be highly labor-intensive. Load cell monitor data could also potentially spoofed using artificial weights. Smith, Labrun and Labella assess that LCM's main benefit would be its ability to directly verify the absence of the undeclared feed (and excess production) scenario, as well as protracted diversion,[17] over its ability to detect HEU production. In recent years, an LCM software tool has been developed for monitoring UF_6 transfer operations at the French Georges Besse-II GCEP, primarily to the efficiency of material accountancy.[18] LCM is rarely conceived as a dedicated measure for verifying the absence of higher-than-declared enrichment levels.

[15] J.M. Whitaker, M. Laughter, and J. Howell, "Using Process Load Cell Information for the IAEA Safeguards at Enrichment Plants," IAEA-CN-184/116, Proceedings of the 2010 IAEA Safeguards Symposium (Vienna: International Atomic Energy Agency, 2010).
[16] Smith, Labrun and Labella, "Potential Roles for Unattended Safeguards Instrumentation…," 55.
[17] Ibid.
[18] P. Richir et al., "Development and Functionalities of a Software Tool to Perform the Monitoring for Safeguards Activities of Gas Centrifuge Enrichment Plants Making Use of Load Cell, Accountancy Scale and On-line Mass Spectrometer Plant Data," Proceedings of the 58th Annual Meeting of the Institute of Nuclear Materials Management (Indian Wells, CA, 2017).

UCVS: The Unattended Cylinder Verification Station, currently in development in the United States, would automatically measure the total uranium mass, ^{235}U mass, and enrichment of feed, product and tails cylinders entering and leaving a GCEP, as well as cylinders moving between material balance areas (MBAs) at the site. Use of the UCVS, thus, would automate many of the materially accountancy tasks performed by inspectors during PIV and IIV activities, thereby improving safeguards efficiency. UCVS mass measurements could also be used to independently verify data from accountancy scales shared by the operator with inspectorates. The technologies that can be used for UCVS are under development and were recently field tested at a fuel fabrication facility in the United States.[19] While UCVS primarily addresses material accountancy efficiency, such a system may also uncover evidence of HEU production via imbalances in mass flow rates. UCVS may not provide a rapid detection time, however, as a substantial lag time often exists between when cylinders are filled and removed from process areas. Product cylinders, in particular, require a few days to cool following homogenization.

Smith, Lebrun and Labella[3] argue that OLEM, LCM and UCVS together would provide much improved effectiveness of safeguards, by respectively verifying the absence of higher-than-declared enrichment values, undeclared feed and protracted diversion, and by conducting both total uranium and ^{235}U mass balances in near real time. These unattended technologies would also provide improved efficiency, most evidently because an effective UCVS system, combined with effective containment and surveillance measures, could allow UF_6 cylinders to be shipped from a GCEP without prior verification via on-site inspections. UCVS would also, as a consequence, provide the non-proliferation benefit of reducing the normal on-site inventory of enriched UF_6 and,

[19] L. Eric Smith et al., "Viability Study for an Unattended UF_6 Cylinder Verification Station: Phase I Final Report," PNNL-25395 (Pacific Northwest National Laboratory, May 2016).

in conjunction with appropriate containment and surveillance, provide the inspectorates with more current knowledge of this inventory.

In principle this suite of technologies could detect the scenarios outlined in Section 2 if an operator allows feed, product, or tails material to pass through OLEMs in a modified unit, or does not tamper with load cell monitors (which would be recording off-normal feed and withdrawal rates for that unit). However, an operator may attempt to evade detection. An evasion scenario could involve blocking off and circumventing OLEMs before misuse takes place, so that the OLEMs only "see" enrichments reflecting normal operating conditions at the facility. In addition, an operator could tamper with load cell data (which cannot yet be authenticated by inspectorates), so that it reflects normal operating conditions, either by falsifying the data directly, or by using artificial weights to spoof the unloading and loading of UF_6 cylinders. A lack of LEU product cylinders being fed through one or multiple UCVS systems might indicate anomalous activity, but as these cylinders may not instantly be transported from the process area to the storage area once they are filled, evidence of facility misuse from a UCVS may only become indicative after production of many SQs of HEU has taken place. For example, under normal conditions, filled product cylinders might undergo homogenization in autoclaves in the process area, requiring a few days thereafter to cool.[20] Thus, detection of this scenario would depend on data from Load Cell Monitors, which themselves are not fully independent measurement sources.

Given the vulnerabilities of OLEM, LCM and UCVS to spoofing, it may be useful to consider supplementary verification measures. It is likely that implementation of only a subset of these

[20] J. Michael Whitaker, "Uranium Enrichment Plant Characteristics – A Training Manual for the IAEA," ISPO-310/R1 (U.S. Program for Technical Assistance to IAEA Safeguards, 2005).

systems would be both necessary and acceptable in terms of cost to the inspectorate and facility operator. Use of these measures would need to be undertaken with a graded approach, depending on the capacity and technology of the specific enrichment plant, the results of acquisition path analysis for the State (which considers the presence or absence of a broader conclusion providing increased assurance of the absence of undeclared nuclear material and activities in a State), and the degree, if any, of international management and engagement. These systems would complement the existing safeguards framework, which includes PIV, IIV, containment and surveillance measures, and Complementary Access for the IAEA in Additional Protocol States, and LFUA in HSP States (and cascade access regimes in non-HSP States, including in China,[21] Brazil,[22] and daily cascade access in Iranian facilities under the JCPOA[23]). At present, some LFUAs take place in conjunction with routine inspection visits, while others are scheduled on a random basis, entirely separate from routine inspections. In addition to these types LFUA that are already implemented, data from multiple unattended systems indicating off-normal conditions at a GCEP could provide impetus for an LFUA inspection of process areas, through which inspectors would verify the actual status of operations at the facility. The latter application of LFUA authority (or the relevant cascade access authority in non-HSP States) would be of critical importance for maintaining UMS devices, and for responding to data indicating off-normal operations at a facility.

In the misuse scenarios described in this chapter, however, all of the unattended safeguards measures could be circumvented (particularly if only 'go/no-go' signals are transmitted) if the

[21] A. Panasyuk et al., "Tripartite Enrichment Project: Safeguards at Enrichment Plants Equipped with Russian Centrifuges," IAEA-SM-367/8/02, Proceedings of the 2001 IAEA Safeguards Symposium (Vienna: International Atomic Energy Agency, 2001), 5.
[22] See Chapter 7 for a detailed discussion of the IAEA's cascade access authority in Brazilian GCEPs.
[23] "Joint Comprehensive Plan of Action" (Vienna, July 14, 2015), Annex I, para. P.71.

operator were to falsely declare that one or more units were being taken off line for maintenance, as the non-operation of portions of a facility could plausibly explain concurrent 'no-go' signals from unattended remote equipment. If this were to happen under normal operation with sufficient frequency, for example during the start-up of a GCEP, or regularly for preventive maintenance, it would be onerous for an inspectorate to follow up each time, possibly accessing relevant cascade hall (and using an LFUA) in order to confirm that no misuse was underway. Thus, it may also be very desirable for inspectorates to have unattended means to quickly detect the reconfiguration of piping, in order to minimize requests for time-consuming inspections that are expensive for both the inspectorate and the operator. Below, a potential toolbox is presented from which an inspectorate might select, with the cooperation of a GCEP operator and relevant State or regional authorities, depending on the characteristics of a particular enrichment plant.

Unit Header and Feed/Withdrawal Flow Monitors: Unattended technology for measuring the flow velocity of UF_6 at the location of the OLEMs and/or the feed/withdrawal stations could be developed. The possibilities range from non-intrusive but quite complex, such as using a pulsed thermal neutron source to drive fission and detecting the delayed arrival of fission products downstream, to intrusive but simple, such as installing a differential pressure measurement device across a restriction in the header pipe.[24] A number of technologies between these two extremes might be envisioned, perhaps based on sound wave propagation upstream vs. downstream in the UF_6 gas. The load cell spoofing and blocking off of OLEMs discussed above, however, could be made ineffective through the installation of flow monitors at feed/withdrawal stations and at

[24] J.N. Cooley et al., "Model Safeguards Approach and Innovative Techniques Implemented by the IAEA at Gas Centrifuge Enrichment Plants," Proceedings of the 48th Annual Meeting of the Institute of Nuclear Materials Management (Tuscon, AZ, 2007).

OLEM installation points. Thus, a combination of OLEMs plus reliable unit header and feed/withdrawal station flow measurements would constitute a powerful verification tool. Like data from load cell monitors, however, information from these flow monitors may give rise to commercial sensitivity concerns, and attention must be paid to maintaining the confidentiality of data measured by these devices. To mitigate data security concerns, flow measurement devices could be designed, as has been done previously, to transmit only binary 'state-of-health' and 'go/no-go' signals to the inspectorate.

Unattended Detection of Reconfiguration: Inspectorates, via a facility design information provided by the operator and State or Regional safeguards authorities, should be aware of the presence of all sample ports installed in cascade halls and in exterior process areas where pipes carry UF_6 to and from unit headers. Inspectorates should be able to identify combinations of these sample ports that could be used to re-pipe cascades into parallel/series configurations of concern, such as those identified in Section 2. It may be possible to install tamper-indicating seals with remote transmission capabilities on critical ports, and an operator may agree to inform the inspectorate prior to accessing these ports. If an unusual number or combination of these critical ports were accessed, this could be an additional factor for inspectorates to consider in deciding whether to request an on-site inspection. As noted in Chapter 7, the agreed HSP approach explicitly permits the application of seals on valves and flanges inside the cascade area, pending State approval via the site's Facility Attachment.

Cascades can also be reconfigured through the installation of new ports. Inevitably this process would result in exposure of some UF_6 to water vapor, resulting in the release of uranyl fluoride

particles, and hydrogen fluoride gas. At the initial reconfiguration, when an inspectorate would remotely detect this activity in order to provide timely detection and deterrence, the uranyl fluoride will not be enriched beyond the design value of the plant, so – for the purpose at hand – detection of HF is just as valuable as detection of UO_2F_2. This is fortuitous because HF is much more easily and quickly detected, and less easily contained than locally deposited uranyl fluoride particles. HF may also be released if an attempt is made to install a flow loop through a flow monitor and OLEM in order to spoof legitimate readings, while routing process material around the monitors. Commercial Open Path Gas Detection systems based on eye-safe lasers can sample path lengths greater than 100m.[25] Some study will be required to optimize a system, and to determine the degree to which an operator can avoid HF production, but it may be possible, by careful location and design, to detect the breaching of relevant piping with high confidence, while not suffering false alarms due to routine operations such as cylinder replacement. Measurements of atypical HF emissions, particularly those that are remote from declared feed and withdrawal points, could potentially be used to help motivate on-site inspection activities, possibly featuring LFUA.

Surveillance cameras could be installed by inspectorates to verify the absence of piping reconfigurations, in cases where this activity would be physically apparent (as opposed to facilities where cascade piping and valves can be remotely rearranged without any externally visible signatures). Cameras could be positioned to view relevant cascade headers and piping leading to and from the unit headers, but without revealing sensitive information. Software could be used to detect changes in configuration and the presence of personnel, and indicate such changes and personnel presence, without releasing images of the piping configuration. This would parallel, in

[25] See, for example, "Hydrogen Fluoride Gas Laser Detection," Senscient, accessed September 15, 2016, http://www.senscient.com/hydrogen_fluoride_detection.html.

effect, measures currently used by inspectors during cascade hall access, where visual inspection is compared against photo albums of the verified configuration, stored at the facility under the seal of the inspectorate. Again, it would be important to confirm an extremely low false alarm rate, as well as high probability of detection. Weaker but simpler alternatives (or complements) would be to use motion detectors rather than cameras, or to aim cameras to view the near vicinity of the piping, required to access the piping, but not the piping itself.

Monitoring of UF_6 Transfer: While the low density of material in centrifuges and cascade piping makes it challenging to measure neutrons even from cascades of centrifuges,[26] cylinders containing kilogram quantities of highly enriched UF_6 produce neutrons at much higher rates, as well as indicative gamma spectra. During the misuse scenarios described in Section 2, as well as in other related scenarios, unattended neutron and gamma detectors permanently located at F/W stations could effectively detect the presence of LEU at feed and tails withdrawal stations, and HEU at product withdrawal stations. The appendix to this dissertation features a study on the use of large-area neutron detectors in F/W areas for this purpose. A proliferator, then, may choose to entirely avoid using installed F/W stations to service modified portions of a facility, and instead feed and withdraw uranium using takeoff points in the header connection area, or within a cascade hall. These undeclared feed and withdrawal points could also be detected with unattended neutron and gamma measurements. Unattended neutron and gamma portal monitors could be located at access points to the header connection area and to cascade halls. More speculatively, between inspections, robots could be programmed to "rove" through the relevant regions of enrichment plants, carrying both neutron and gamma detectors. Alternatively, monitors could be configured to travel on rails

[26] Pickrell et al., "Detection of Illicit HEU (^{235}U) in a Fuel Cycle Enrichment Plant."

above areas where illicit cylinders could be concealed. If a mobile monitor were to detect anomalous radiation signatures, or was prevented from entering a normally accessible area, it could signal this situation. This would provide motivation (likely along with other detected signatures) to call for an on-site inspection. If such an inspection featured an LFUA, inspectors could also carry radiation detection instruments to verify the absence of hidden UF_6 cylinders.

Timely Data Transmission: Operators are sensitive to the detail and rate of data transmission from their facilities, both to avoid proliferation of sensitive technology, and to protect their commercial interests. Thus, it will be necessary to limit the transmission of data, and likely even the accumulation of data within the systems discussed here. Although much more analysis is required, it appears that a simple two-bit transmission from each deployed monitoring instrument indicating state-of-health and "nominal operation" or "human verification required," perhaps every 6 hours, might be sufficient. As with the choice of technologies from the proposed toolbox, the frequency of data transmission should be graded, in this case depending particularly on the potential rate of production of weapons-grade material.

5. Timely Response

The IAEA has at its disposal two tools for timely detection and response. The first is the ability to hold an on-site inspection with LFUA at facilities in HSP States. This gives IAEA inspectors, with as little as two hours' notice, access to cascade halls at enrichment plants. Although LFUA inspections are typically held either in conjunction with routine inspections or on a random basis, if the IAEA were to detect off-normal activity through multiple independent signals, an LFUA could also be justified. Since it is unlikely that many large GCEPs will be constructed in the

immediate future, and since those that are constructed are likely to be located in or near states with other facilities under IAEA safeguards, designated inspectors could be stationed so as to be able to arrive promptly. The capacity and technology of the specific enrichment plant, the results of Acquisition Path Analysis, the presence of a Broader Conclusion in the host state and the degree, if any, of international management and engagement should be taken into account by the IAEA in deciding on a request for a short-notice LFUA, versus further inquiries and discussion. It is clearly of the utmost importance, for the credibility of the IAEA and for the efficient operation of enrichment plants, that measurement-driven requests for short-notice LFUAs be extremely infrequent. In non-HSP States with safeguarded GCEPs, cascade access may be afforded pursuant to each site's Facility Attachment.

If evidence of significant misuse were to be detected during on-site inspection activities, or inspector access were to be inhibited, the Department of Safeguards would attempt to resolve the situation on a technical basis, first at the sectional or divisional management level, but while informing the Deputy Director General for Safeguards, and the Director General. In the absence of a satisfactory resolution, the Director General might contact the Foreign Minister of the state in question and request an expeditious resolution. As an ultimate step, the Director General could call a meeting to consult with the IAEA Board of Governors on very short notice, even a few hours, thus effectively making the situation public knowledge. The possibility of such a chain of events should function as a powerful deterrent.

6. Summary

Modern large-scale gas centrifuge enrichment plants present a substantial challenge to the goal of timely detection and deterrence of the production of weapons-grade uranium. The steps of reconfiguration, equilibration and production of the first SQ of weapons-grade uranium would be slower than an ideal SWU calculation of production rate would suggest. However, reconfiguration to produce HEU could perhaps be accomplished very quickly, perhaps in a few hours, and the subsequent production rate could be large. This reality is a potential threat to the current regime for verifying the absence of higher-than-declared enrichment levels and HEU production, which relies almost entirely on random visits to cascade areas, in general via LFUA. Greater use of unattended remote monitoring systems, as a complement to LFUA, will mitigate this situation. Some of these systems (i.e. OLEM) have reached limited deployment, while others (LCM and UCVS) have been under development.

Further technologies should be considered, nevertheless, in order to provide the inspectorates with a sufficient toolbox to implement the depth required for timely decision-making, based on multiple signal paths. In particular, flow measurements to complement OLEMs and LCMs would be highly desirable. Remote-indicating seals on key declared sample ports, and hydrogen fluoride detection to provide indication of the installation of new, undeclared ports may be appropriate. Cameras with change-detection software, or simple motion detectors, could be simple but effective tools. Neutron and photon detectors at F/W stations and at key portals, even roving detectors, could be considered in order to detect illicit F/W stations in a timely fashion. These technologies would provide added depth for a toolbox from which an inspectorate could select, depending on the capacity and technology of the specific enrichment plant, as well as factors specific to the State in

which a GCEP is located, including the results of Acquisition Pathway Analysis, the presence of a Broader Conclusion in the host state and the degree, if any, of international management and engagement. Use of these systems would still be coupled to inspectorates' authority to perform on-site inspections featuring cascade access, especially the IAEA's authority to use LFUA in HSP States. The ability of safeguards inspectorates to inform the international community of unexplained signatures of misuse, in particular HEU production, should function as a powerful deterrent against this activity.

This widespread deployment of UMS at commercial GCEPs, however, will be challenging to achieve. Past experiences with the Cascade Header Enrichment Monitor (CHEM) and the Continuous Enrichment Monitor (CEMO) demonstrate how technical and political obstacles can complicate the rollout of novel verification technologies, to the point where their impact on safeguards effectiveness is nearly negligible. The issue of equality in safeguards obligations between States, which was a fundamental part of the HSP's Sydney Compromise, may again become politically salient, particularly concerning Iran after the expiration or termination of JCPOA measures. Thirty-five years after the end of the HSP, preventing the dissemination of sensitive enrichment technology information is still of critical importance, and technology holders (as exemplified by Brazil) have striven to limit the transfer of this information to inspectorate personnel. All of these factors will complicate efforts to strengthen GCEP safeguards. The following chapter concludes this dissertation by considering the factors that created the current state of GCEP safeguards and next steps for ensuring the effectiveness of GCEP safeguards in the future.

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Chapter 9 – Considering the Future of Gas Centrifuge Enrichment Plant Safeguards

This dissertation has studied technical and political dynamics that guided the course of gas centrifuge enrichment plant (GCEP) safeguards, stretching from centrifuge enrichment's days as a fledgling technology, up to the present day, where GCEPs dominate the enrichment market. From this history, it is clear that as a result of political discord in the 1970s and 1980s among GCEP safeguards stakeholders, safeguards concepts for verifying the absence GCEP misuse, including those for verifying the absence of highly enriched uranium (HEU) production, have been conceived primarily through political means, leaving technically motivated detection probability and timeliness goals as secondary considerations. Since the early 1980s, when the Hexapartite Safeguards Project (HSP) took place, the ability of safeguards inspectorates to detect this type of facility misuse in a timely manner has diminished. As GCEPs have grown larger in capacity, development and deployment of commensurate safeguards capabilities has been slow. This dynamic has led to a gap between contemporary safeguards needs and capabilities. Now is the time to consider filling this gap.

Within each chapter of this dissertation, further observations and conclusions can be drawn. These takeaways can and should be used to inform future efforts to improve GCEP safeguards. Before discussing these points, however, it is worth recapitulating the main events and findings from individual chapters.

Chapter 2 provided an overview of the legal and technical means by which GCEPs safeguards are conducted, both under the International Atomic Energy Agency (IAEA) and the European Atomic Energy Community (Euratom). In doing so, it was shown that while legal provisions and terminology for material accountancy are explicitly defined, the roles and authority for inspectorates regarding misuse verification are more nebulous, both under the 1957 Euratom Treaty, and under the IAEA's Model Comprehensive Safeguards Agreement (INFCIRC/153). As a result, the nature of GCEP misuse verification activities, if there were to be any at all, would be up for debate as talks on the issue began in the early 1970s.

Chapter 3 provided historical context for the environment in which these talks commenced. In particular, it is notable that not only had no GCEP been under international safeguards, but no uranium enrichment facility had ever been subject to international safeguards by the time the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) went into force in 1970. Members of the club of GCEP technology holders were concerned about commercial espionage. In addition, GCEP technology in the Netherlands, the Federal Republic of Germany (FRG), the United Kingdom and the United States was subject to a strict security classification regime that the United States imposed in 1960. Although the three European States (known as the 'Troika') and the United States had engaged over classification policy since then, very little dialogue—even informal talks—took place prior to the first meeting convened by the IAEA on GCEP safeguards in 1972. The United Kingdom made substantial efforts to dampen GCEP safeguards engagement between the Troika and the United States, as well as between the IAEA and the United States in the early 1970s. Meanwhile, the United States espoused concern that the Soviet Union and its allies could stoke fears about FRG nuclear weapons intentions, if GCEP safeguards were perceived to be weak.

Chapter 4 covered the first period of multilateral activity on GCEP safeguards. This period was marked by bitter disputes, not only between inspectorates and technology holders, but also between technology holders themselves. From 1972 onwards, a rift emerged between the Troika and the United States over the Troika's highly minimalistic, UK-developed Parry Paper safeguards concept, and the thorough and complicated American perimeter safeguards approach. Stark differences developed between American and European interpretations of key provisions in INFCIRC/153. Although the Troika eventually agreed to allow the United States to field test perimeter safeguards equipment at the Almelo GCEP, this program was far less extensive than originally envisioned by the Americans and produced results of meager value. Nevertheless, all four States agreed that inspector access to GCEP cascade areas would be highly undesirable, and collectively guided the IAEA, which was poorly equipped with technical knowledge on GCEP capabilities, to commit to developing a GCEP safeguards model without cascade access. Meanwhile, as non-access was used as a working basis for IAEA GCEP safeguards, Euratom management aggressively pushed for access for its own inspectors at Almelo (even though individual Euratom inspectors may have been more sympathetic to the Troika position), arguing that cascade access was necessary to verify the absence of facility misuse, and eventually winning out in late 1973. The dispute between Euratom and the Troika over cascade access led to a delay in signature of the IAEA-Euratom Safeguards Agreement and led to the creation of an example Facility Attachment (FA) for Almelo that effectively committed the IAEA to non-access. Thus, by the mid-1970s, two conflicting precedents for GCEP safeguards existed between the two international safeguards regimes: one under Euratom, where unlimited inspector access was

deemed necessary for effective verification, and the other under the IAEA, still to be determined, where inspectors would be barred from cascade areas.

Chapter 5 examined efforts in the late 1970s, driven by the entry into force of the IAEA-Euratom Safeguards agreement, to finalize a GCEP safeguards approach. By this time, additional technology holders, both NPT Nuclear Weapon States and Non-Nuclear Weapon States, had made plans to construct GCEPs. During this period, the IAEA backed out of its commitment to the non-access approach. Shortly after the IAEA and technology holders affirmed the non-access principle at an IAEA Advisory Group meeting in 1977, the IAEA began Design Information Verification work for the Almelo GCEP. Now armed with on-the-ground facts, the IAEA reversed course, and pushed for cascade access during routine inspections. As a result, long-overdue discussions towards the Almelo FA ground to a halt, and three IAEA Consultants' Meetings held in 1979 failed to make any meaningful progress towards a resolution. Meanwhile, the positions of the individual Troika States began to diverge: while the UK and FRG prioritized the need to restrict inspector access to protect sensitive information, the Netherlands, frustrated by nearly a decade of failed talks and facing ultimate responsibility for safeguards issues at Almelo, was more willing to yield to the IAEA's requests. Meanwhile, a rift developed between Troika States over whether the IAEA was tasked with verifying the absence of undeclared material and enrichment capacity under NPT safeguards, with the FRG taking a firm position that this objective lay out of the IAEA's scope and that as a result, cascade access would be unnecessary. This deadlock drove creation of the HSP as a dedicated, time-limited effort to resolve the cascade access issue once and for all.

Chapter 6 examined the dynamics of the HSP itself. The HSP's treatment of misuse verification and the cascade access question was dominated by political gamesmanship. In order for the HSP to succeed, a political understanding first had to be found regarding the question of whether safeguards activities should verify the absence of undeclared material and enrichment capacity. A nebulous understanding was first achieved in Boekelo, the Netherlands in early 1981, which proved to be ineffective. Attempts in mid-1981 to discuss technical papers on cascade access concepts proved to be fruitless, owing to the unresolved dispute over the IAEA's authority to verify the absence of undeclared material and activities. In November 1981 in Tokyo, under the initiative of HSP Chairman Fred Brown, parties finally agreed that the HSP would not explicitly address undeclared feed and enrichment capacity, allowing the project to proceed into its second year. Once limited frequency unannounced access (LFUA) to cascade areas had been chosen as the favored approach, the FRG in particular (among other participants, including the UK and Japan) made a concerted effort to trade LFUA implementation for political reassurances. The FRG's strategy was particularly apparent in the drafting of the HSP Assessment Group report, in which it sought to forge a potential path forward for a non-access approach if its political demands were not met, as well as in the agreement of the Sydney Compromise of early 1982.

The HSP's ultimate success depended on the fulfillment of the Sydney Compromise, which entailed three conditions. Most of the HSP's work during its second year focused on accomplishing this task. The first condition obliged all HSP parties to accept and equally apply the LFUA model (with LFUA application at the U.S. GCEP in Portsmouth, OH being especially consequential). The Sydney Compromise also called for explicit definition of measures used under LFUA. Key parameters, however, including NDA measures and cascade access frequency, were themselves

agreed via political compromise. Negotiation of nondestructive analysis (NDA) measures to be used under LFUA in mid to late 1982, primarily between the FRG, UK and Japan on one side and the United States on the other, proved to be intensely political, delaying the conclusion of the HSP itself by months. Resolution of security concerns implicated by cascade access, the third Sydney condition, spawned the creation of an informal system for GCEP inspector selection within the IAEA. While the HSP considered technical characteristics of facilities and of safeguards equipment in depth, the available evidence suggests that LFUA was nevertheless crafted through political compromise. Despite its largely political origins, LFUA both provided inspectorates with the authority to verify the absence of misuse at GCEPs in a credible and efficient manner, while also limiting the intrusiveness and frequency of cascade hall inspections to levels acceptable to reluctant technology holders.

Chapter 6 highlighted other dynamics, besides the course of events and conditions that led to the successful resolution of the HSP. Two stand out. First, it is apparent that the United States and Troika participants, despite decades of engagement on international safeguards, and nearly ten years of engagement specifically on GCEP safeguards, failed to establish a fundamental basis on which to conceptualize cascade access activities. The United States tasked its national laboratories with developing safeguards equipment, and based its verification concept on this technology, conceiving of parameters such as access frequency as functions of technology portfolio being used. The Troika accomplished the same task by working backwards: the Troika first outlined various access regimes, each with varying constraints, and then identified the technology that could be used under each regime. The lack of common ground between U.S. and Troika access concepts

inhibited the ability of the HSP to address LFUA measures on a technical basis, leading to the aforementioned compromises on NDA and inspection frequency.

A second dynamic from the HSP concerns the effect of multinational nuclear fuel cycle enterprises on safeguards negotiations. From Chapter 6, it is clear that the HSP severely strained the relationship between the three Treaty of Almelo parties, which at the project's outset had attempted to participate as one bloc. One year into the HSP, the Netherlands, frustrated by the FRG's attempts to obstruct the HSP's work over the undeclared feed and capacity issue, threatened to direct the negotiation of an Almelo FA unilaterally, in violation of the Treaty of Almelo. This tension was the result of divergences on GCEP safeguards within the Troika that had formed prior to the HSP, which brought them to the fore. Nevertheless, had the HSP Chairman not intervened in Tokyo to bury the undeclared question, the continued survival of the Troika itself would likely have been in jeopardy.

Chapter 7 assessed the effectiveness of the LFUA concept as agreed at the end of the HSP, and found that even at a 1000 tSWU/a plant for which it was conceived, the probability with which it could detect the production of a significant quantity (SQ) of highly enriched uranium (HEU) sometime in a given year was 10–28%, assuming that no visible signatures of misuse would exist after HEU production had taken place, the absence of environmental swipe sampling (which was the case in the early 1980s), and assuming that traditional material accountancy would not uncover evidence of misuse in a timely fashion. This finding supports the argument that the LFUA likely provided a substantial deterrent for GCEP misuse at the time at which it was created, even though it, like material accountancy, did not provide a particularly timely means for detecting misuse. The

focus of the chapter then switched to studying developments to GCEP safeguards since the HSP. Although significant efforts have been dedicated to improving means for detecting facility misuse, little has been effectively achieved in improving inspectorates' abilities to detect HEU production. While the IAEA and Member States devoted resources to develop header enrichment monitoring technology, the systems that were developed were plagued by technical problems, faced political opposition to their implementation, and perhaps with the exception of on-line enrichment monitor (OLEM) implementation in Iran, have done little to improve the efficiency or effectiveness of GCEP safeguards. Environmental sampling, although powerful as a 'smoking gun,' is less effective for detecting excess enrichment levels in a timely manner. The Additional Protocol, while useful for detecting enrichment activities at clandestine sites, does little to aid inspectorates in detecting misuse of a declared facility, and the IAEA's improved model approach of the mid-2000s only (but finally) addressed undeclared feed. Meanwhile, the cascade access problem reared its head again in the new millennium, this time in a non-HSP State: Brazil. Thus, the overall conclusion of this chapter was that while much attention has been given to developing inspectorate capabilities for detecting GCEP misuse in general, in the realm of detecting excess enrichment levels and HEU production—the most critical and consequential aspect of GCEP misuse—the results have been meager.

Chapter 8 shifted to a fully technical perspective, evaluating the potential for misuse at modern commercial enrichment facilities, which are now approximately four times larger than those conceived by the HSP in the 1980s. At a 4000 tSWU/a GCEP, it is at least technically conceivable that an abrupt breakout, including time required before and afterwards for cascade equilibration, could take place in as little as two days. If the international community deems it necessary to detect

this activity as it is taking place, thus denying a malicious actor an abrupt "breakout" capability—the ability to produce and clandestinely store weapons-usable material before other verification means (e.g. environmental sampling or material accountancy) raise the alarm—new verification capabilities are needed. Use of unattended monitoring systems (UMS) with remote data transmission will mitigate this situation. A menu of UMS options is presented in the chapter, and a study on a system for monitoring UF_6 transfer operations at feed and withdrawal stations is presented in the Annex to this dissertation.

Now is the time to think seriously about improving GCEP safeguards measures for the timely detection of HEU production and excess enrichment levels. While the situation today is problematic, the stakes will only rise higher in the future. First, although the global enrichment supply is not expanding currently, it may need to do so within the next few decades to fuel a growing civil nuclear power sector. Although the IAEA predicts that in a "low case," nuclear generation growth for the foreseeable future may be close to nil, growing from 383 GW of installed capacity in 2015 to 417 GW in 2050, the IAEA's "high case" predicts that nuclear energy may comprise 598 GW of capacity by 2030, and 898 GW by 2050.[1] Each additional 100 GW of nuclear generation will require an additional 8,500–18,000 tSWU/a in global enrichment capacity.[2] Even if nuclear power growth proves to be modest (although higher than the "low case"), enrichment capacity will have to expand. This need for growth will almost certainly be satisfied via new GCEP capacity (assuming that no unforeseen breakthrough in the viability of large-scale laser enrichment occurs) and is likely to involve the expansion of existing facilities, or the construction of new

[1] International Atomic Energy Agency, "Nuclear Technology Review 2017," GC(61)/INF/4 (Vienna, August 2017), 9.
[2] This assumes that each gigawatt of electrical capacity requires 25 metric tons of uranium enriched to between 3% and 5%, which form the lower and upper bounds for the SWU capacity estimate.

plants that are larger than existing ones that are under safeguards. Some States may also elect to build GCEP capacity in excess of global demand levels, in order to guarantee a domestic enrichment supply. With time, as enrichment facilities grow, the challenge of detecting HEU production in a timely manner will only become more pressing.

Nevertheless, even in a world where nuclear generation capacity remains at today's levels—or even falls—the effectiveness of GCEP safeguards will still continue to be increasingly important. Although Iran's centrifuge enrichment capacity is heavily restricted under the JCPOA, this provision has a lifetime of only ten years, and will expire in 2026.[3] Iran is only obligated to accept the use of OLEM devices, again under the JCPOA, until 2031, the same year in which LEU feedstock restrictions will expire.[4] In addition, if the JCPOA is terminated early, Iran will no longer be bound by enrichment capacity restrictions. Regardless of Iran's intentions, when Iran is free to construct unlimited centrifuge enrichment capacity, the robustness of the IAEA safeguards system will fall under ever more scrutiny, particularly with respect to its ability to detect HEU production in a timely manner. Once JCPOA measures expire or are terminated, limits on enrichment capacity and feedstock will be extremely difficult or impossible to renegotiate.

If an agreement is made in the future to ban the production of HEU, either as part of a Fissile Material Cutoff Treaty or as a standalone agreement, the safeguards capabilities discussed in this dissertation will become applicable to GCEPs in Nuclear Weapon States. The world's largest GCEP, located in Novouralsk, Russia, reportedly had a nominal capacity of approximately 13,300

[3] "Joint Comprehensive Plan of Action" (Vienna, July 14, 2015), Annex 1, para. F.27.
[4] Ibid., Annex 1, paras. N.67.1, J.56.

tSWU/a, as of 2015, at which time its cascades were undergoing upgrades.[5] If international safeguards were to be applied at this facility, or one of a similar size, it would highly likely that a suite of UMS would be necessary in order to allow for timely verification of the absence of HEU production.

Up to this point, however, this dissertation has not explicitly considered potential obstacles to the implementation of new UMS capabilities at GCEPs. Ignoring these future challenges would be an oversight. If anything is to be gathered from the history of GCEP safeguards presented in this dissertation, it would be that misuse verification is anything but purely technical. Since plans were first made to build two 25 tSWU/a pilot facilities in the Netherlands, the issue of GCEP safeguards has served as a battleground for disputes over interpretations of INFCIRC/153 provisions, equality in safeguards obligations, the use of various measurement technologies and inspector access rights, while causing massive friction within the multinational enrichment effort established by the UK, the Netherlands, and the FRG. This dissertation has also shown that facility operators, along with State and regional safeguards authorities and other national policymaking bodies, have considerable power to shape the safeguards activities that are undertaken by inspectorates. Although the relevant national and regional safeguards authorities are beholden to international safeguards verification, inspectorates rely on States themselves, as well as facility operators, to make it possible for them to carry out their work, both at high political levels, as well as in the minutiae of safeguards implementation. The 'nuts and bolts' of safeguards also depend on a close relationship between facility operators, State and regional authorities, and inspectorates. The use of safeguards equipment in a facility, for example, may depend on a matter as menial as whether

[5] International Panel on Fissile Materials, *Global Fissile Material Report 2015* (2015), 20, 48.

a suitable and appropriately located electrical outlet exists for powering a given device. Without the cooperation of a facility operator, an inspectorate would be bereft of this information. Without the cooperation of facility operators and safeguards authorities, inspectorates would have no declarations to verify. Without funding from national governments, inspectorates would cease to function. Thus, it is crucially important that safeguards activities be mutually satisfactory to all stakeholders and facilitate a constructive relationship between all parties.

The JCPOA itself may be a complicating factor in the rollout of UMS technology. Both the preamble to the JCPOA[6] and the operative portion of United Nations Security Council Resolution 2231[7] state that JCPOA provisions should not be used as precedents for rights and obligations for NPT safeguards, as well as for principles of international law. Thus, there may be resistance to the continuation or use any measures contained in the JCPOA in States other than Iran, as well as within Iran after JCPOA measures cease or are terminated. For example, even though the IAEA derives its authority to use on-line enrichment monitoring from regular comprehensive safeguards agreements (see INFCIRC/153, paragraph 74(e)) and has used the technology previously for routine safeguards, because on-line enrichment monitoring is cited explicitly in the JCPOA, some States will likely argue that it should be excluded from routine safeguards use. This argument may be extended to other novel forms of UMS, exacerbating efforts to strengthen GCEP safeguards.

[6] "Joint Comprehensive Plan of Action," para. xi.
[7] United Nations Security Council, Resolution 2231, S/RES/2231 (2015), para. 27.

Lessons from the Past

Future efforts to improve GCEP safeguards must avoid the pitfalls that stymied GCEP safeguards discussions in years past, while cultivating the conditions that moved the same discussions forward. Four observations and recommendations are offered in this regard:

Observation 1: *Inspectorate Secretariats need to be equipped at all relevant staffing levels with the necessary in-house technical knowledge to come to their own conclusions on safeguards needs and capabilities.*

Recommendation 1: *Inspectorate Secretariats should be able to independently assess and defend their safeguards needs. Technology holders and inspectorates must collaborate to ensure that the parts of inspectorates that handle enrichment safeguards are staffed by personnel with backgrounds in uranium enrichment. Technology holders must continue to keep inspectorates apprised of new technical developments relevant to uranium enrichment safeguards.*

As discussed in Chapter 3, in the early 1970s, the IAEA was not endowed with the technical knowledge it needed to independently evaluate safeguards requirements for gas centrifuge enrichment facilities. As a result, the IAEA was led by technology holders, on the basis of their information, to commit to a non-access approach for GCEP safeguards, a position that it had to reverse once confronted with design information for Almelo. Had the IAEA not committed in the first place to basing GCEP safeguards on non-access models, arguing a case for cascade access at Almelo, once equipped with design information, would likely have been far easier.

While the evidence suggests that Euratom's management caught on quickly to the need to verify the absence of GCEP misuse, it is unclear whether its inspectors, at least prior to the first Almelo cascade inspection in 1973 and particularly during the Almelo inspection of July 1973, were on the same page. While Euratom was equipped with the legal authority to successfully pursue its case, mixed messages from its management and inspectors on the purpose and frequency of cascade access sowed confusion over Euratom's intentions among its Member States and primed the cascade access issue for further politicization in the late 1970s, when cascade access under IAEA safeguards fell into dispute.

This observation does not suggest that either inspectorate lacks the technical capacity, either at management or inspector levels, to make independent judgements regarding safeguards needs at present. Today, technology holders serve as a critical source of information for safeguards inspectorates. This flow of information, however, must continue, and must be facilitated by all technology holders possessing GCEPs under international safeguards. In the future, if an inspectorate is not apprised of technical developments at a facility under their watch, not only will it be hampered in its ability to carry out effective verification for lack of full knowledge of the GCEP's technical capabilities, it may also risk being fed information that is detrimental to safeguards effectiveness at the site. Both results, and the latter, in particular, would be unacceptable. In addition, inspectorates and technology holders should collaborate to ensure the continued presence of inspectorate staff with backgrounds and knowledge in uranium enrichment, particularly those with operator experience.

The intended result of free and candid sharing of nuclear fuel cycle technology information is that inspectorate Secretariats should be able to not only objectively assess their safeguards needs, but also defend them to the Member States that oversee them, to generate political support for Secretariat initiatives. A secondary benefit to open knowledge sharing is that inspectorates will also be as fully aware as possible of legitimate constraints on safeguards activities that can be implemented, given the particularities of individual facilities, and thus more sensitive to operator needs and concerns. Finally, while the continued exchange of technical information is important for the continued effectiveness of GCEP safeguards, it is also vital for safeguards on new fuel cycle technologies. If laser enrichment becomes commercially feasible, for example, States and operators must ensure that inspectorates have sufficient expertise to make independent safeguards decisions, avoiding any ill-informed commitments to precedents that require reversal at a later date.

Observation 2: *The existence of multinational fuel cycle enterprises can complicate the negotiation of safeguards provisions.*

Recommendation 2: *Responsibility for negotiating safeguards arrangements should be delegated to individual stakeholder States (e.g. facility host States) under future multinational enrichment enterprises.*

Multinational fuel cycle arrangements, including the construction of enrichment plants designed, built, owned, staffed, and/or operated by multiple countries, have long been understood as beneficial to nuclear nonproliferation. The arguments that support this understanding, which lie

out of the scope of this study, are not contested here—it should be noted that one of the key benefits of the tripartite enrichment effort, at the time of its founding, was that it provided the FRG an opportunity to continue developing GCEP technology without building a GCEP in its territory, which would likely have been an extremely provocative act in the eyes of the Soviet Union and its allies. However, this dissertation does contend, on the basis of dynamics within the Troika during the HSP, that the presence of a multinational fuel cycle agreement can be a complicating factor in negotiating safeguards measures for a given facility. The HSP, especially during its first year, was a cause of political friction within the Tripartite Joint Committee (JC), as the FRG and Netherlands pursued different priorities—while the FRG's main goal was to push for the non-access approach with no provisions for undeclared feed and material, the Netherlands sought to implement whatever approach was favored by the inspectorates, which by then was the cascade access model. These tensions harmed working relationships between Troika government personnel managing the partnership, and on at least one occasion, led to a complete breakdown in the Troika's efforts to coordinate its members' negotiating strategies at the HSP.

The presence of the Troika, in addition, also slowed the progress of the HSP. At the beginning of the HSP, only two of its six participant States—the FRG and Japan—were fully opposed to cascade access and the applicability of safeguards to undeclared material and capacity, although the UK was somewhat sympathetic to this position. However, in the early days of the HSP, the FRG and the UK held considerable sway over the common Troika position, burying initial attempts by the Netherlands to speak in favor of cascade access. Instead, the Troika made pushed for limiting the scope of the HSP so as to eliminate the consideration of safeguards objectives that would necessitate cascade access, for example framing what became the Boekelo Understanding. In

effect, the existence of the Troika amplified what was, from the beginning of the HSP, a minority position. Had the Troika members entered the HSP as independent States (in a world without the Treaty of Almelo), the Netherlands would almost certainly have initially been more vocal in support of cascade access, and consensus in support of the access approach would likely have developed more quickly.

Again, while making no prejudgments on the overall value of multinational fuel cycle approaches to nonproliferation, it should be expected that stakeholders in such an enterprise will have differing priorities, with respect to international safeguards. While a State responsible for centrifuge and cascade design is likely to be more sensitive to information security issues, the State in which a multinational facility is located might be more concerned about the credibility of the agreed verification approach, to mitigate the concerns of other States and actors over whether the facility is being legitimately used. As with the Troika during the HSP, complicating effects can go both ways: safeguards talks may create tensions within the multinational organization, and the organization itself may serve to amplify opposing viewpoints during safeguards negotiations. Policymakers would be well advised to anticipate these effects and prepare to mitigate them. If a multinational enrichment enterprise is established in the future, its stakeholder States would be wise to give thought to assigning roles and responsibilities for managing their relationship with relevant inspectorates. Giving facility host States the prerogative to negotiate safeguards measures could help avert some of the problems faced by the Troika and the HSP.

Observation 3: *Development of novel safeguards technology is not an end in itself—its usability, versatility and utility in meeting safeguards objectives matter.*

Recommendation 3: *Safeguards technology be conceived with safeguards objectives and fieldability in mind, as well as the variety of environments in which it may be used.*

It is old news to safeguards policy experts that all forms of safeguards technology, in order to be fieldable, must satisfy a variety of conditions. It must address a safeguards objective. Devices must not be overly expensive. They must be reliable. Disruption to facility operations must be minimal. Unattended remote systems must have minimal false alarm rates. New systems should improve, or at least not detract from, safeguards efficiency—in other words, use of novel technology to address a given safeguards objective must not require more in-field inspection time than doing the same task by hand. None of these statements lie outside the bounds of common knowledge today, although it is important to highlight that these considerations, as always, must be heeded. Safeguards instruments, above all, must be usable.

These familiar constraints explain why some enrichment safeguards technologies, including those developed and envisioned for the U.S. perimeter safeguards and cascade access concepts, as well as the Cascade Header Enrichment Monitor (CHEM), failed to see extensive use. In all three cases, the technology entailed excessive inspection effort, was expensive to implement, and was disruptive in some degree to operator activities. Given current goals for safeguards technology development today, it is not surprising that these concepts met little success.

The reasons for the failure of more modern systems to see extensive use, however, are more complicated. The Continuous Enrichment Monitor (CEMO), for example, was designed to address

a specific safeguards need that had emerged at newly flexible GCEPs, but was not routinely used outside the UK, which developed the device. CEMO remedied many of the faults that marred CHEM's usability, and on the basis of the criteria listed above, should have been more widely accepted. While German political opposition seems to have been instrumental in keeping CEMO from being used at Gronau, the failure of CEMO to catch on is also attributable to its incompatibility with piping at Almelo. If, in line with this dissertation's recommendations, UMS is to reach widespread deployment at safeguarded GCEPs, these systems must be developed to be compatible across a broad array of plants. Novel technologies should be designed not only be usable, but also versatile, and this consideration should be taken into account at the outset of design work. Additionally, if GCEP UMS equipment is easily adaptable for use at multiple facilities, requiring only minor modifications or variants to suit the characteristics of each plant, meeting the next recommendation will also be easier to achieve.

Observation 4: *Reciprocity can be a powerful tool.*

Recommendation 4: *Well-established technology holders should consider offering to implement novel GCEP safeguards technologies on a reciprocal basis with newer technology holders.*

Universal implementation of LFUA at GCEPs in all HSP States, and particularly at the U.S. GCEP in Portsmouth, OH, was critical to the HSP's success. Chapter 6 showed that the initial U.S. overture to limited cascade access in late 1981 was pivotal in convincing the UK to support the LFUA model, which ultimately drove the FRG to accept LFUA. Furthermore, fulfillment of the HSP's Sydney Compromise, and thus implementation of LFUA, was predicated on the principle

of its equal application among all HSP participants. In the exchange of letters that followed the HSP, Australia, the FRG, Japan, the Netherlands and the UK explicitly committed themselves to LFUA on the condition that the same would be implemented at Portsmouth. LFUA at GCEPs in every HSP State meant that each technology holder would be exposed to the risks inherent with exposing safeguards inspectors to sensitive enrichment technology. Mutual exposure to risk, however, was not the end goal of this arrangement. Instead, equal application of LFUA in all HSP States, under the condition of reciprocity, meant that all parties would be invested in mitigating some of the risks inherent with cascade access, ultimately reducing them. All HSP parties would share responsibility to ensure that sensitive information was appropriately handled by inspectorates. Moreover, all six technology holders would be explicitly accountable to each other, and not only to the inspectorates, to demonstrate a continued commitment to effective safeguards at GCEPs.

The same principles should apply to the future rollout of UMS at GCEPs. The use of new UMS at long-established GCEPs should encourage State authorities and operators of newer facilities to be more willing to accept these devices. Installation of the OLEM at Almelo, where the system was previously field tested, could signal to newer technology holders that a more established GCEP State is not only willing to be subject to similar levels of scrutiny, but is also willing to buy in further as a UMS stakeholder. Technology holders with UMS installed at their GCEPs would share responsibility in ensuring that the systems implemented in a cost-efficient manner, with minimal false alarm rates and with minimal disruption to facility operations. Without a display of willingness from longstanding technology holders to subject themselves to unattended monitoring, thereby taking an active interest in maximizing the efficiency of its application, States like Iran

(post-JCPOA) and Brazil would be unlikely to do the same. In short, reciprocity will be key to implementing UMS at GCEPs, and established technology holders will likely have to make the first move.

Taking the Next Steps

At present, there exists an appetite for the development of UMS for GCEPs among Western technology holders. The United States has recently invested considerable resources in the development of OLEM and UCVS, as well as other more experimental unattended monitoring techniques that have not seen safeguards use,[8] and has historically been a leader in the development of novel GCEP safeguards approaches and technologies, stretching back to the days of perimeter safeguards and the Minor Isotope Safeguards Technique. Meanwhile, unlike in earlier times, Troika governments and Urenco have become critical partners in field testing devices that have shown promise, both those that were designed indigenously, and those developed in other States. Among technology holders, there exists no dearth of capacity to develop UMS for GCEP safeguards. Indeed, some devices—i.e. the OLEM—are already approved for safeguards use and should not require substantial technical effort to be readied for facilities other than those where it is used currently. Thus, the main challenge to strengthening GCEP safeguards will not be technical barriers, but political acceptance of widespread UMS among technology holders and facility operators.

[8] See, for example, Mark M. Pickrell et al., "Detection of Illicit HEU (^{235}U) in a Fuel Cycle Enrichment Plant," Proceedings of the 47th Annual Meeting of the Institute of Nuclear Materials Management (Nashville, TN, 2006).

Indeed, the most prominent thread in this dissertation has been that GCEP misuse verification has been subject to considerable political influence. Given the political context in which inspectorates—particularly the IAEA—operate today, it will be difficult to negotiate and codify misuse verification under quantity, timeliness and detection probability criteria to the same degree as material accountancy verification. HSP States, which have now lived with the current system for over three decades (and which are globally perceived and perceive themselves as posing a minimal proliferation risk) will be reluctant to abandon the framework that they negotiated for one likely involving more onerous safeguards obligations. Meanwhile, newcomer GCEP States will perceive such a change as a cynical ploy conceived by more established technology holders to derail their fledgling centrifuge development and commercialization efforts. Hard and fast criteria may be used by some States to stonewall any measures taken by inspectorates that may provide a capability that exceeds the agreed detection probability or timeliness goal. At some point in the future, if political conditions improve (perhaps through unforeseeable events, akin to the discovery of the Iraqi weapons program in the early 1990s), inspectorates and their Member States should explore explicitly defining a target detection probability for HEU production associated with quantity and timeliness goals. Although explicit detection criteria may be a worthy goal, at the moment, however, this will be extremely difficult to achieve. In the meantime, less rigid measures should be explored for strengthening GCEP misuse verification through the rollout of UMS, which are discussed below.

If reciprocity will be crucial to improving GCEP safeguards in the future, it may be worth considering whether it would be productive to organizing a dedicated technical project involving all current technology holders, akin to the original HSP. This approach, however, dubbed here as

"HSP2" is unlikely to be optimally productive. While the results of an HSP2, if successful, would receive broader acceptance than piecemeal progress in single or groups of technology holders, a universal forum would also entail considerable risks. For example, LFUA is currently a widely accepted and integral part of GCEP safeguards in HSP States, which make up the majority of technology holders with safeguarded GCEPs. The right of inspectorates to conduct LFUA, at least where it has already been agreed, should be preserved. The introduction of Brazil to an HSP2 could introduce pressure to backslide on the LFUA provision, given that cascade access for IAEA inspectors in Brazil is currently more restricted than it is in HSP States. If an HSP2 were to end without agreement, this would serve to entrench the status quo, making it harder to advance GCEP safeguards than it would have been to do so before. Political scrutiny of inspectorates, especially the IAEA, is higher today than it was in the early 1980s—at present, in a forum with several States as diverse as the United States and Iran, the ability of inspectorates to advocate for safeguards effectiveness and efficiency on a purely technical basis would be restricted. For these reasons, an "HSP2" would likely be unwise.

An initiative by inspectorates themselves to roll out UMS across technology holders, however, would also be unlikely to gain traction. The most recent safeguards strengthening effort by the IAEA Board of Governors, Committee 25, which aimed to strengthen the IAEA system as a whole, stalled in the mid-2000s amidst a lack of collective political will among Member States. In addition, the current set of GCEP technology holders include States that have voiced strong skepticism over the IAEA Secretariat's recent work to implement the State Level Concept, and thus an additional push by the IAEA to push these States to make additional commitments would be untimely.

There exists a better option for expanding the role of UMS than an inspectorate-led effort or a technical forum of all inspectorates and technology holders. Direct engagement between individual technology holders offers more promise. This arrangement would offer a path for States to negotiate allowing extended use of UMS at GCEPs on a reciprocal basis, while averting the risks inherent in an HSP2-type forum. These commitments could subsequently be formalized via an exchange of letters between State governments and the applicable inspectorates, as well as a third-party guarantor State, if necessary. Although inspectorates are generally not at liberty to disclose safeguards measures and activities are used in specific States and facilities, States involved in the letter exchange could elect to publicize the fact that extended UMS are being used at GCEPs within their borders, and special arrangements could be made for inspectorates to share their experiences implementing GCEP UMS in confidence, among relevant State stakeholders. If a State were to fail in its commitment to implement UMS, a possible response could be an increase in the frequency of unannounced cascade visits at the GCEP in question. One possible first step forward could be for one of the Troika members to offer OLEM implementation at its facility, in exchange for the same in Brazil. Closer to the expiry of inspection measures specified in the JCPOA (which include on-line enrichment monitoring and the use of electronic seals), which will take place in 2031, at which point further UMS will have been developed (including, for example, flow monitors and perhaps mobile neutron detectors, either fixed on rails or free-roving), the United States, with approval of the Tripartite JC, could offer to implement these systems at the Urenco USA facility in Eunice, NM, along with on-line enrichment monitoring, on a reciprocal basis with Iran.

This dissertation has shown the vast extent and depth of the political challenges that States and inspectorates have faced over the history of GCEP safeguards. These issues have greatly complicated efforts to develop technically effective verification approaches for these facilities. Further improvements to safeguards verification at modern centrifuge enrichment facilities will be difficult. Given the connection between uranium enrichment and the acquisition path to a nuclear weapon, however, the stakes are high. Furthermore, with larger facility capacities and with ever increasing political scrutiny of inspectorate capabilities in the present day, the stakes are getting ever higher. Although taking steps to strengthen GCEP safeguards may be arduous and will neither make headlines nor bring public goodwill to policymakers, the potential cost of not doing so is too great to ignore.

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Annex – Unattended ^{235}U Feed and Withdrawal Monitor for Gas Centrifuge Enrichment Plants

This annex has been presented as M.E. Walker, R.J. Goldston and A. Glaser, "Unattended ^{235}U Feed and Withdrawal Monitor for Gas Centrifuge Enrichment Plants," Proceedings of the 58th Annual Meeting of the Institute of Nuclear Materials Management (Indian Wells, CA, 2017).

1. Introduction

International safeguards organizations face a particular challenge in implementing verification activities at modern, commercial-scale gas centrifuge enrichment plants (GCEPs). Inspectorates must not only verify the non-diversion of nuclear material, as is necessary for safeguards at other nuclear fuel cycle facility types, but must also verify the absence of facility misuse. In a GCEP misuse scenario, a facility may be used to enrich uranium hexafluoride (UF_6) beyond its declared maximum enrichment level, potentially up to levels suitable for use in a nuclear explosive device. Inspectorates must be able to detect misuse in a timely fashion, thereby deterring such activity through the risk of early detection.[1] Given the large capacities of modern GCEPs, however, detection of an abrupt misuse episode at such a facility must take place on a very short time scale, in order to be timely. In a recent study, two of this paper's authors estimated that a GCEP with a nominal 4000 tSWU/a capacity, typical of commercial facilities under international safeguards today, may be used to produce as many as 29 significant quantities (SQ) of highly enriched uranium (HEU), as defined by the International Atomic Energy Agency (IAEA),[2] enriched in excess of 90%, in approximately one week. This assumes sufficient stock of 5%-enriched feed

material is available to be fed into 90% of the existing cascades, and requires only a simple modification to the feed and withdrawal lines of 10% of the cascades. The equilibration period for the new configuration is of order hours.[3]

The development and expanded use of unattended monitoring systems for GCEP safeguards[4] will help safeguards inspectorates address this timeliness challenge. In this paper, we present studies on the use of an unattended neutron detection system for verifying the transfer of ^{235}U into and out of the enrichment process in feed and withdrawal cells at a GCEP. The primary purpose of such a system would be to assure, in near-real time, that only natural uranium is being fed into enrichment cascades, and that only depleted uranium tails are being withdrawn. In general, feeding on-hand low-enriched uranium (LEU) into an enrichment cascade dramatically reduces the time it takes to produce a given amount of HEU.

Neutron emission from a given amount of UF_6 is largely dependent on the mass of ^{235}U in the material, as the production of (α,n) neutrons on fluorine is largely driven by the abundance of ^{234}U in the material, which increases essentially linearly with the ^{235}U enrichment at about a 1% ratio of $^{234}U/^{235}U$, except for cases of reprocessed material, and material that has been re-enriched from depleted uranium. Neutron source intensity calculations by SOURCES4C,[5] assuming a mass density of 5.09 g/cm^3, yield an (α,n) source of 0.071 neutrons/s-cm^3 for 0.3 wt%-enriched material, rising nearly linearly to 1.1 neutrons/s-cm^3 for 5 wt%-enriched material, taking into account alpha decay of ^{234}U as well as small contributions from ^{235}U and ^{238}U**.** Spontaneous fission, primarily of ^{238}U, contributes approximately an additional 0.045 neutrons/s-cm^3 for enrichments in this range. Using this relationship, it is possible to verify that only natural uranium is being fed into

enrichment cascades, and that only depleted uranium is being withdrawn in the tails, by measuring absolute neutron count rates, as well as the changes in count rates over time, at portal monitor-type moderated neutron detectors positioned near feed and withdrawal cells. We note that the prior misuse calculation[3] showed only a moderate change in ^{235}U withdrawal rate in the product line. While there exists some dependency of neutron emission rates on the geometrical arrangement of UF_6 inside cylinders (which affects both self-shielding and neutron multiplication), we find that the proposed measurement principle is nevertheless robust.

The proposed system uses moderated boron-lined proportional counters very similar in design to neutron detector modules developed for use in radiation portal monitors. MCNP6[6] simulations have been carried out to study the behavior of the proposed detector module in measurement scenarios involving 30B and 48Y UF_6 cylinders containing a variety of material enrichments and inner material configurations. We have also included a spoofing scenario in which a 48Y cylinder containing LEU is shielded in an attempt to appear to contain natural uranium. This paper presents the results of these simulations.

2. Proposed Neutron Detection System

We have based our proposed neutron detection system on a module developed by GE Reuter Stokes for use in radiation portal monitors. The GE Reuter Stokes module uses twenty tubular boron-lined proportional counters,[7] each 71" in length and 1" in diameter, housed in a 1' x 5" x 7' block of high-density polyethylene (HDPE) moderator. Pacific Northwest National Laboratory (PNNL) modeled and tested this system in a laboratory setting in 2012, and detailed specifications

and complete component dimensions of the detector module are provided in report number PNNL-21501.[8] The detector tubes used by PNNL were fabricated from aluminum. Although the composition of the enriched boron lining and fill gas of the detector tubes is proprietary, the PNNL study found that modeling the tube lining in MCNPX as a 0.75 μm-thick layer of pure ^{10}B produced results comparable to those obtained in laboratory measurements. A gas composition of 90% argon and 10% carbon dioxide (by volume) was assumed in the PNNL report.

An MCNP6.1 model of the detector assembly, using the same assumptions made in PNNL's MCNPX model, was constructed. Absorption of neutrons and subsequent generation of products of the $^{10}B(n,\alpha)^{7}Li$ reaction in the boron layer was modeled using MCNP's Neutron Capture Ion Algorithm (NCIA), by setting the *coilf* parameter to 5 on the *phys:n* data card (this turns on NCIA, but leaves light ion recoil off). Detector pulses were modeled using an FT8 neutron capture tally in the boron lining, with the *edep* option implemented. With the *edep* option turned on, MCNP6 only records a capture event when a separate specific tally for the same particle history (in this case, an *F8 energy deposition tally for heavy ions and α particles in the active volume of the proportional gas) exceeds a specific threshold, which was set to 50 keV. Thus, a detector pulse is only recorded when the resulting ^{7}Li ion or α particle from a neutron capture deposits more than 50 keV in the proportional gas (since these two must be ejected in opposite directions, only one can enter the gas). All particle transport and reactions were modeled in analog, so calculated variances reflect those that would occur in an actual measurement.

To check the validity of the new MCNP6 detector model, simulations were carried out using a ^{252}Cf source shielded by 0.25" of lead, surrounded by a 1" HDPE shell, identical to the source

setup in PNNL's laboratory measurements, but excluding the source's support structure, for simplicity. In the first simulation, the source was positioned 1 m from the center of the front face of the detector module containing the detector tubes, and in the second simulation the source was positioned 2 m away. Both simulations used 1.5042×10^7 source particles, analogous to a 5-minute measurement time for the 11.75 μCi ^{252}Cf (21.4 ng) source used by PNNL. Results of these simulations, given in count rate per nanogram of ^{252}Cf, show acceptable agreement with data from 5-minute measurements acquired by PNNL using four different detection modules, as shown in Table A-1.

Table A-1: Comparison of count rates in a 20-tube GE Reuter Stokes detector module from laboratory measurements and simulated MCNP6 measurements of a shielded and moderated ^{252}Cf source (measurement time: 300 s).

Source distance (m)	PNNL Results (Lintereur et al., 2012)[9]		MCNP6.1 Results (cps/ng ^{252}Cf)
	Detector module	cps/ng ^{252}Cf	
1	Module 1	8.01 ± 0.035	8.419 ± 0.036
	Module 2	8.08 ± 0.035	
	Module 3	8.45 ± 0.036	
	Module 4	8.05 ± 0.035	
2	Module 1	2.88 ± 0.021	2.700 ± 0.020
	Module 2	3.08 ± 0.022	
	Module 3	3.1 ± 0.022	
	Module 4	2.99 ± 0.021	

For UF6 cylinder measurements, it was determined that a lower detector efficiency would be acceptable, given the source intensity and proximity of UF6 cylinders to the detectors in the proposed use case. Fewer detector tubes would also reduce the cost of the detector assembly. Thus, in subsequent simulations with UF6 cylinders, only seven tubes were used the detector assembly: three in a row near the front of the detector, and four near the back, instead of a respective 7-6-7 arrangement for front, middle and back rows of the 20-tube assembly. Cross-section illustrations of the 20-tube and 7-tube detector assemblies are shown in Figure A-1. Note that the 7-tube system is identical to the 20-tube system, except that it contains 13 fewer tubes, and the spaces that the

eliminated tubes occupied are filled with HDPE. MCNP6.1 simulations constructed using the same ^{252}Cf source described above yielded an absolute efficiency for the 7-tube detector assembly of about 40% of that of the 20-tube assembly.

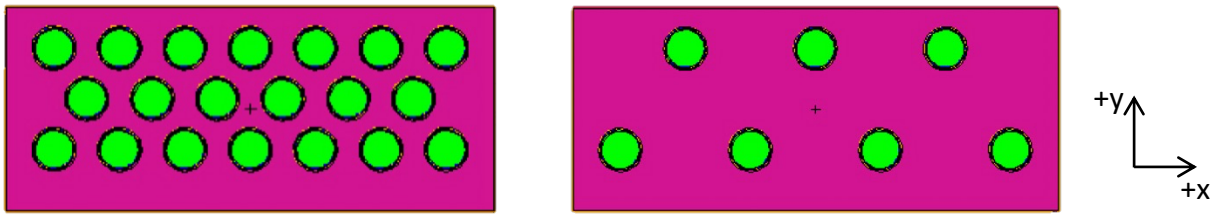

Figure A-1: Cross-section illustrations, taken in the X-Y plane, of 20-tube (left) and 7-tube (right) assemblies of GE Reuter Stokes boron-lined proportional tubes. The origin is marked with a cross in both images. Polyethylene is shown in magenta, and the proportional gas is shown in green. Boron lining, tube walls and a small air gap between the tubes and polyethylene appear together as black lines around the detector tubes. The detector assemblies are oriented so that the front faces of both panels appear on the top of the figure. The centerline of the front row is 1" from the front face of the panel and the centerline for the back row is 2.5" behind that of the front row. Detector tubes are laid out symmetrically about the y-axis, and evenly spaced within each row. In the 7-tube case, the distance from the center of each tube to the center of the next is 3.22". (A detailed description of the 20-tube system is given in PNNL-21501.)

3. Modeling Singles Neutron Count Rates from UF_6 Cylinders

After establishing the validity of the MCNP6 detector modeling technique against the laboratory data in PNNL-21501, MCNP6 models were produced using UF_6 cylinders as neutron sources, to determine how neutron count rates measured by the detector assembly behave as cylinders are emptied and filled. The absolute neutron count rate at an occupied feed or withdrawal cell is an indicator of the amount of ^{235}U inside, and the change in count rate over time is indicative of the flow rate of ^{235}U in and out of the cell. These two metrics, taken together, can be used to infer whether or not enriched material is being fed into the enrichment process. For example, when a cylinder is placed in a feed cell, the absolute count rate in a nearby detector will jump up immediately. As material is fed into the cascade, the count rate is expected to fall. Feeding LEU

into a system, however, will result in far more ^{235}U (and thus more ^{234}U) leaving the cylinder per unit time, resulting in a more precipitous drop in count rate than when natural UF_6 is fed. The feeding of LEU may also result in LEU being collected in tails cylinders, as in the misuse scenario previously modeled.[3] If this were to happen, a neutron detector positioned nearby would record both a faster-than-normal uptick in count rate, but also eventually a much higher absolute count rate than would be expected for a tails cylinder containing depleted UF_6. These principles are the physical basis for our proposed system.

ANSI standards[10] for UF_6 cylinders were used to produce 30B and 48Y container models in MCNP. Both cylinder models were constructed using ASTM A516 steel, Grade 60. At modern enrichment facilities, product LEU is most commonly stored and shipped in 30B cylinders, while depleted tails and natural feed is stored and shipped in larger 48Y cylinders. 30B cylinders are designed with a maximum fill capacity of 2277 kg UF_6, while 48Y containers can hold up to 12500 kg UF_6. These values do not represent the maximum possible capacity of the cylinders, however, as solid UF_6 expands when it is liquefied: liquid UF_6 at 110˚C occupies 53% more volume than solid UF_6 at 20˚C.[11] Thus, solid UF_6 in a cylinder filled to maximum capacity occupies significantly less than the cylinder's total volume.

For each simulation, a container containing solid UF_6 was positioned with its cylindrical axis parallel to the horizontal (xy) plane, with a single detector assembly positioned to the side of the container, 2 m away from the container's geometric center. In the vertical (z) dimension, each cylinder was positioned so that its inner centerpoint lay on the same horizontal plane as the vertical

midpoint of the detector tubes. Illustrations of the simulation geometry for full 48Y cylinders are given in Figure A-2.

As mentioned in the introduction, the profile of UF_6 inside the containers has an effect on self-shielding, neutron moderation, and neutron multiplication, and thus affects both the intensity and energy spectrum of emitted neutrons. While the actual geometry of material in containers may be quite complex, featuring also nonhomogeneous density,[12] a study[13] by Berndt, Franke and Mortreau indicates that the largest difference in neutron detector response exists between an annular profile, in which solid UF_6 is arranged along the inner wall of the cylinder, and a bottom-up filling profile. An annular profile may form when UF_6 is directly desublimed into a cylinder at a low temperature. Conceivably, a bottom-up profile may form following homogenization of a cylinder, after liquid UF_6 returns to the solid phase. A combination of both profiles may appear in cylinders filled with UF_6 gas at room temperature,[14] or following heating of a cylinder for sampling. In this study, to represent the limiting cases, both the annular and bottom-up profiles were modeled. For the annular case, the thickness of the UF_6 layer was assumed to be even.

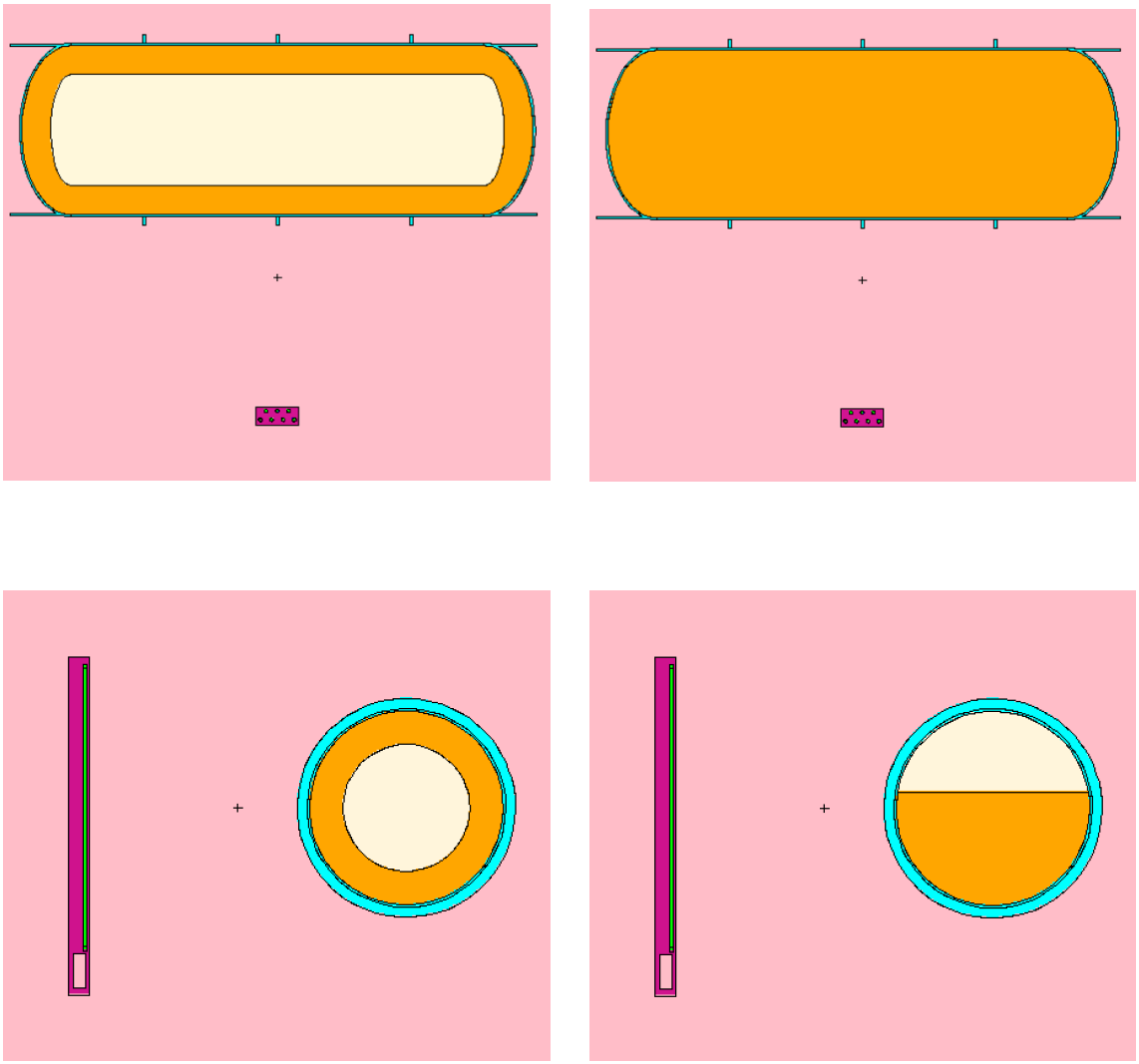

Figure A-2: Illustrations of measurement geometry for a 48Y cylinder filled with solid UF_6 to maximum capacity, in annular (left) and bottom-up (right) filling profiles. Images on the top are taken in the x-y plane, while lower images depict a cross-section taken in the y-z plane. UF_6 is shown in orange, steel container walls are shown in light blue, air is shown in pink, and nitrogen gas is shown in cream.

Table A-2: Simulated count rates in a 7-tube detector assembly positioned 2 m away from the centerlines of 30B and 48Y UF_6 cylinders containing various fill levels, fill profiles, and material enrichments. Each simulation used 10 million source neutrons.

Cylinder type/ enrichment (wt%)	Source strength (n/s-cc)	Fill level	Annular fill profile			Bottom-up fill profile		
			UF_6 Layer Thickness (cm)	Equivalent measurement time (s)	Count rate (counts/s)	UF_6 fill depth (cm)	Equivalent measurement time (s)	Count rate (counts/s)
30B, 3%	0.67499	**Full**	11.9	33.41	149.01 ± 2.11	41.93	33.15	109.86 ± 1.82
		3/4	8.3	44.52	117.56 ± 1.62	33.53	44.31	82.45 ± 1.36
		1/2	5.2	66.86	78.43 ± 1.08	25.03	66.34	50.78 ± 0.87
		1/4	2.5	132.06	39.32 ± 0.55	15.53	132.72	23.33 ± 0.42
30B, 5%	1.09729	**Full**	11.9	20.55	241.94 ± 3.43	41.93	20.39	189.29 ± 3.05
		3/4	8.3	27.39	189.65 ± 2.63	33.53	27.26	135.17 ± 2.23
		1/2	5.2	41.13	128.72 ± 1.77	25.03	40.81	85.27 ± 1.45
		1/4	2.5	81.24	63.09 ± 0.88	15.53	81.64	38.30 ± 0.68
48Y, 0.3%	0.1176	**Full**	21.0	34.80	82.55 ± 1.54	71.16	34.65	61.15 ± 1.33
		3/4	14.7	46.11	73.87 ± 1.27	56.86	46.20	47.90 ± 1.02
		1/2	9.1	69.81	56.47 ± 0.90	42.36	69.15	32.12 ± 0.68
		1/4	4.3	140.00	30.64 ± 0.47	26.16	138.59	16.36 ± 0.34
48Y, NatU	0.20252	**Full**	21.0	20.21	148.74 ± 2.71	71.16	20.12	109.58 ± 2.33
		3/4	14.7	26.77	132.71 ± 2.23	56.86	26.83	82.64 ± 1.76
		1/2	9.1	40.54	98.43 ± 1.56	42.36	40.16	56.75 ± 1.19
		1/4	4.3	81.30	52.15 ± 0.80	26.16	80.48	29.57 ± 0.61
48Y, 3%	0.67499	**Full**	21.0	6.06	537.13 ± 4.37	71.16	6.04	396.05 ± 8.10
		3/4	14.7	8.03	455.89 ± 7.53	56.86	8.05	298.54 ± 6.09
		1/2	9.1	12.16	334.46 ± 5.24	42.36	12.05	198.37 ± 4.06
		1/4	4.3	24.39	175.14 ± 2.68	26.16	24.15	97.74 ± 2.01
48Y, 5%	1.09729	**Full**	21.0	3.73	966.75 ± 16.10	71.16	3.71	707.92 ± 13.81
		3/4	14.7	4.94	777.13 ± 12.54	56.86	4.95	531.16 ± 10.36
		1/2	9.1	7.48	545.31 ± 8.54	42.36	7.41	353.51 ± 6.91
		1/4	4.3	15.00	286.11 ± 4.37	26.16	14.85	159.36 ± 3.28

MCNP input decks were generated for 30B cylinders containing 3 wt% and 5 wt%-enriched uranium, as well as for 48Y cylinders containing 0.3 wt%, 0.7 wt%, 3 wt%, and 5 wt%-enriched material. The latter two cases would reflect highly abnormal feed or withdrawal operations, as 48Y cylinders are typically not filled with LEU. Source neutron spectra were calculated with SOURCES4C. For each cylinder-enrichment combination, detector count rates were calculated with the cylinder filled to approximately 25%, 50%, 75%, and its full capacity. (Because of the geometric complexity of the UF_6 inside the cylinders, and the resulting difficulty of specifying the precise geometric parameters, actual UF_6 masses used in the simulations differ from these values by up to 1%.) The number of source particles for each simulation was set to 10 million. Results of these simulations are given in Table A-2.

It is apparent that the fill profile of cylinders has a considerable effect on count rate. 30B cylinders that are filled bottom-up produce approximately 20-40% fewer counts than containers with annular fill profiles, all else held equal. For 48Y cylinders, this drop is between 25-50% of the count rate for the annular fill profile. Nevertheless, these data indicate that some discrimination is possible for cylinders, based on absolute count rates alone. For example, 48Y cylinders filled to capacity with LEU, of enrichments typical of product material, will induce far higher count rates than any 30B cylinder containing 3-5% LEU. This difference becomes statistically significant to many sigma with a measurement time on the order of seconds. Likewise, 3-5% enriched material in a full (or even a half-full) 48Y cylinder is easily distinguishable from cylinders containing natural or depleted UF_6, by many sigma over measurement time on the order of tens of seconds. 0.3%-enriched material in a full 48Y cylinder is clearly distinguishable by several sigma from natural uranium in a 48Y container filled to ½ capacity or more, with a measurement time on the order of

minutes. However, the use of gross count rates alone is not sufficient for distinguishing between some container types and enrichments – full 30B cylinders containing 3%-enriched material, for example, produce similar count rates as full 48Y cylinders containing natural UF_6, for both the annular and bottom-up fill profiles.

In order to verify that LEU is not being fed into an enrichment cascade from a 30B cylinder, it is also necessary to measure changes in count rates over time (if multiple cylinders are being fed or withdrawn, it is necessary to sum the changes in count rates at feed and withdrawal cells). This observation relies on the fact that if LEU is being fed into a cascade during an abrupt misuse scenario, ^{235}U flow rates in and out of feed and withdrawal cells will be far greater in magnitude than during regular operation of the facility.

To investigate changes in detector count rates over time, three separate scenarios were studied. The first two scenarios each considered normal operation of a 500 tSWU/a (nominal) production unit containing 10 cascades. The first scenario considers production of 3 wt%-enriched material, and the second scenario considers a product enrichment of 5 wt%. Both scenarios assume cascade ideality within the unit, and a tails enrichment of 0.3 wt%. In the third scenario, a 30B cylinder containing 3%-enriched material is fed into the production unit, with a feed rate of 90% of that of the first scenario. This feed rate was chosen on the assumption that nine out of ten cascades could be fed in parallel, and could together feed into the tenth cascade to further increase the enrichment of the product.[15] To represent worst-case scenarios, we assume that five cylinders are being fed into the unit simultaneously and estimate the expected changes in count rate between the first two

hours of feeding operations from initially full cylinders, diminishing the fall in neutron counts relative to total counts.

In order to produce optimal statistics, one could count neutrons from all five cylinders for one hour and then for a second hour, and compare the two total counts. To evaluate this scenario we linearly interpolate between the count rates derived from the MCNP-simulated cylinder measurements presented earlier, as a function of UF_6 mass, and estimate the number of counts that would be recorded during each hour, neglecting background. A plot of these count rates against UF_6 mass in a single cylinder is given in Figure A-3. Although there exists an uncertainty associated with the slope of the interpolated lines owing to the limited number of source particles used in the MCNP simulations, our estimate only considers the Poisson error associated with the number of counts that would be recorded over each hour, as the former error would not be applicable to an actual measurement.

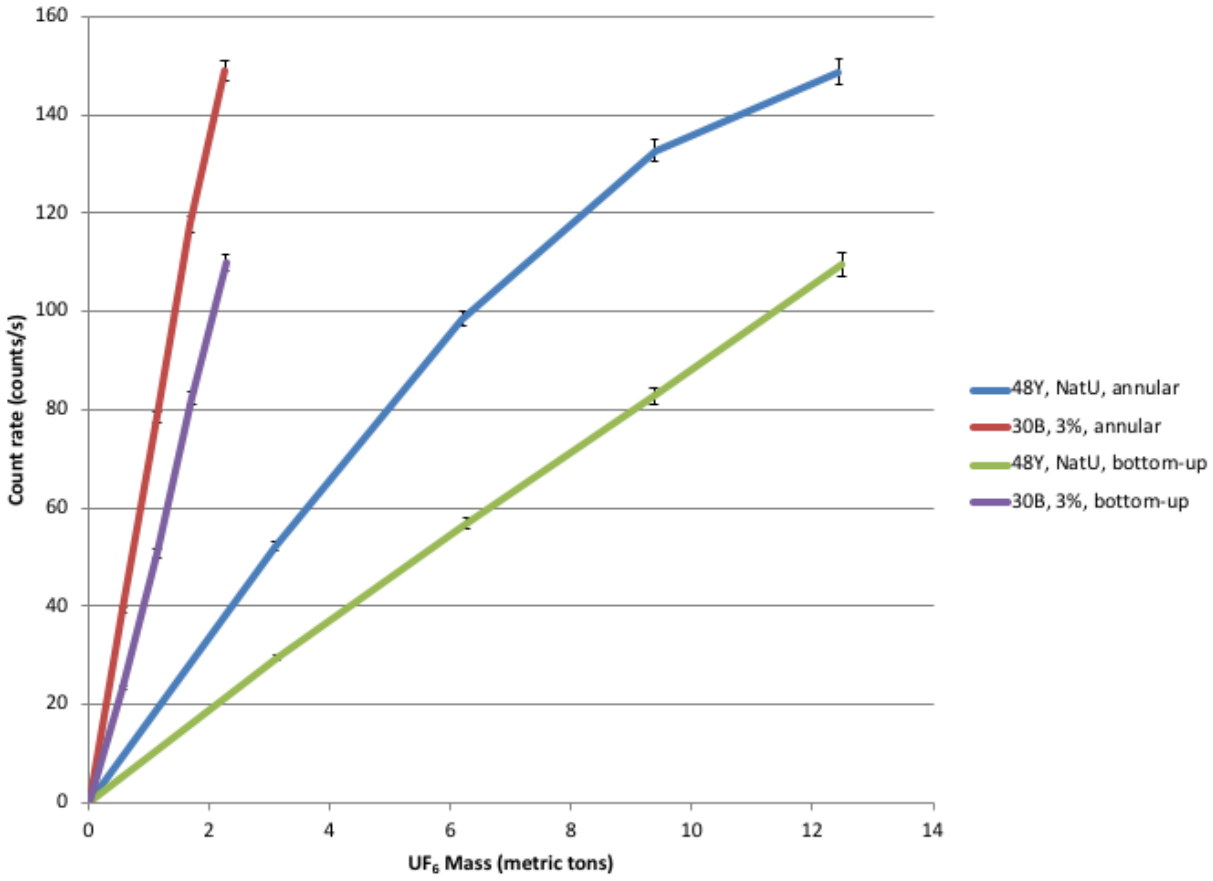

Figure A-3: Expected count rates, as calculated by MCNP, for a 7-tube detector assembly positioned 2 m away from a single UF_6 cylinder. Neutron emission from heels is ignored.

Table A-3: Estimates of the change in neutron counts between two 1-hour periods immediately after UF_6 is withdrawn from 48Y cylinders containing natural UF_6, and a 30B cylinder containing 3 wt%-enriched material.

Cylinder number and type	Enrich-ment (wt%)	Total Feed Rate (kg/h)	Annular fill profile			Bottom-up fill profile		
			Counts, Hour 1	Counts, Hour 2	Change in Counts	Counts, Hour 1	Counts, Hour 2	Change in Counts
5 x 48Y (3 wt% product)	0.71%	109	2.68E+06 ± 1.64E+03	2.67E+06 ± 1.64E+03	2.06E+03 ± 2.31E+03	1.97E+06 ± 1.40E+03	1.97E+06 ± 1.40E+03	3.39E+03 ± 1.98E+03
5 x 48Y (5 wt% product)	0.71%	134	2.68E+06 ± 1.64E+03	2.67E+06 ± 1.64E+03	2.54E+03 ± 2.31E+03	1.97E+06 ± 1.40E+03	1.97E+06 ± 1.40E+03	4.16E+03 ± 1.98E+03
5 x 30B (misuse scenario)	3%	98	2.73E+06 ± 1.63E+03	2.65E+06 ± 1.63E+03	1.97E+04 ± 2.31E+03	1.97E+06 ± 1.40E+03	1.95E+06 ± 1.40E+03	1.69E+04 ± 1.98E+03

From Table A-3, it is clear that feeding of LEU from a 30B cylinder can be easily discriminated from the feeding of natural UF_6 from a 48Y cylinder in the worst-case scenarios portrayed. Over the two hour measurement period, in the annular case, the difference in count rate between the LEU feed scenario and the natural feed scenario with the higher flow rate is about 17200 ± 3300 counts, and with the bottom-up feed profile, this difference is 12700 ± 2800 counts. These differences are statistically different from zero at 5.25 and 4.54 sigma respectively.

If 3% enriched LEU were to be deposited in 48Y cylinders as tails during a misuse scenario at a similar rate as during normal operations, the difference in the change in count rate, relative to the change in count rate during normal operation, would be even greater, due to the fact that neutron emission rates from depleted uranium are lower than those for natural uranium.

4. Detecting A Spoofing Scenario

While the proposed 7-tube detector system is clearly capable of detecting the feeding of LEU from unshielded 48Y and 30B containers, a malicious actor might consider shielding a 48Y cylinder containing LEU so that absolute count rate and changes in count rate recorded by the detector are consistent with a those of a 48Y cylinder containing natural material. This could be done with field-castable, fire- and heat-resistant (to 200˚C) boron-silicone shielding that is commercially available from Shieldwerx, catalog number SWX-237.[16] With a 2×10^8 source particle MCNP simulation, it was calculated that a 7 cm-thick layer of SWX-237 wrapped around a 48Y cylinder containing 3%-enriched material would reduce the total count rate in the detector to 141.19 ± 1.08

cps for the annular profile case, and 115.01 ± 0.98 cps for a bottom-up profile, approximately consistent with the count rates for a full 48Y cylinder of natural UF_6. However, neutron moderation by hydrogen in the shielding will result in the neutron spectrum at the detector assembly's front face being biased towards lower energies, thus increasing the relative efficiency of the front row of detector tubes relative to those in the rear. Back/front count rate ratios for a full, unshielded 48Y cylinder containing natural material, versus a full, shielded 48Y cylinder containing LEU, are given in Table A-4. The latter scenario is easily detectable, as its measured back/front ratio, resulting from neutron moderation in the shielding material, differs by many sigma from the expected back/front ratio for an unshielded 48Y cylinder containing natural UF_6, following a measurement time of 2 minutes. Furthermore, note that the back/front count rate ratios from the simulation results presented in Table A-2 ranged from 0.49 to 0.77, with standard errors between 0.02 and 0.03 (due to the lower number of source particles in those simulations). Thus the back/front ratio for the shielded cylinder of 0.4 represents a strong deviation.

Table A-4: Comparison of back/front count ratios for shielded and non-shielded scenarios. Values were calculated with MCNP6 simulations using 2×10^8 source particles. For the shielded 3% case, this corresponds to a measurement time of about 120 seconds, and for the unshielded natural case, this corresponds to a measurement time of about 400 seconds.

Cylinder/ enrichment level	Initial fill level	Annular fill profile			
		Front row counts	Back row counts	Back/front count rate ratio	Difference in count rate ratio
Shielded 48Y, 3%	**Full**	12192 ± 110	4931 ± 70	0.404 ± 0.007	0.119 ± 0.009
Unshielded 48Y, Natural	**Full**	39266 ± 198	20517 ± 143	0.523 ± 0.005	

Cylinder/ enrichment level	Initial fill level	Bottom-up fill profile			
		Front row counts	Back row counts	Back/front count rate ratio	Difference in count rate ratio
Shielded 48Y, 3%	**Full**	9919 ± 100	3968 ± 63	0.400 ± 0.008	0.117 ± 0.009
Unshielded 48Y, Natural	**Full**	28713 ± 169	14856 ± 123	0.517 ± 0.005	

5. Conclusions and Further Work

The placement of moderated neutron detectors at feed and withdrawal stations offers a simple and robust approach for verifying UF_6 transfer operations at feed and withdrawal cells in gas centrifuge enrichment plants. MCNP6 simulations reported in this paper indicate that a system with approximately 40% of the efficiency of neutron detection modules developed for radiation portal monitors should be capable of providing timely verification that only natural uranium is being fed into enrichment cascades.

In further modeling work, the shielding and neutron moderation effects of the housings of feed and withdrawal cells need to be taken into account, as well as the use of alternative shielding materials in a range of spoofing scenarios. In addition, other detector placements need to be taken

into account – for example, it may be possible to mount detectors lengthwise, above feed and withdrawal cells, instead of vertically by their sides. Spot check simulations with detectors placed lengthwise with respect to the cylinders yielded very similar results. Studies also need to be undertaken on the effects of background and interference from multiple cylinders positioned next to multiple detectors, as would be the case in a feed and withdrawal area. In this case, there will be neutrons counted at every detector from every station, but we anticipate that the sensitivity matrix will be dominated by near-diagonal elements and can be accurately inverted.

Endnotes and References

[1] For example, under Comprehensive Safeguards Agreements made pursuant to the Treaty on the Nonproliferation of Nuclear Weapons (NPT), the stated objective of safeguards is "the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection." See International Atomic Energy Agency, INFCIRC/153 (Corrected), 1972, para. 28.

[2] The IAEA defines a significant quantity of HEU as 25 kg of ^{235}U in HEU. This is "the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded." The IAEA defines HEU as "uranium containing 20% or more of the isotope ^{235}U." See International Atomic Energy Agency, *IAEA Safeguards Glossary, 2001 Edition*, International Nuclear Verification Series No. 3 (Vienna: International Atomic Energy Agency, 2002), 23; Ibid., 32.

[3] Mark E. Walker and Robert J. Goldston, "Timely Verification at Large-Scale Gas Centrifuge Enrichment Plants," *Science and Global Security* 25, no. 2 (2017): 59–79.

[4] L. Eric Smith, Alain R. Lebrun, Rocco Labella, "Potential Roles for Unattended Safeguards Instrumentation at Centrifuge Enrichment Plants," *Journal of Nuclear Materials Management* 42, no. 1 (2013): 38–58.

[5] W.B. Wilson et al., "SOURCES 4C: A Code for Calculating (alpha,n), Spontaneous Fission, and Delayed Neutron Sources and Spectra," LA-UR-02-1839, Los Alamos National Laboratory, 2002.

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[7] "Reuter Stokes Boron-10 Lined Proportional Counter," GE Measurement & Control, 2013. https://www.gemeasurement.com/sites/gemc.dev/files/reuter_stokes_boron-10_lined_proportional_counter_fact_sheet_english_0.pdf.

[8] Azaree Lintereur, Edward R. Siciliano, and Richard T. Kouzes. "Boron-10 Lined Proportional Counter Model Validation," PNNL-21501, Pacific Northwest National Laboratory, June 2012.

[9] Ibid., 8.

[10] "ANSI N14.1-2001: Packaging of Uranium Hexafluoride for Transport," 49 CFR 173.420(a)(1), American National Standards Institute, 2011.

[11] R. Berndt, E. Franke, and P. Mortreau, "^{235}U Enrichment or UF_6 Mass Determination on UF_6 Cylinders with Non-Destructive Analysis Methods," *Nuclear Instruments and Methods in Physics Research A* 612, no. 2 (2010): 312.

[12] L.E. Smith et al., "Viability Study for an Unattended UF6 Cylinder Verification Station: Phase I Final Report, PNNL-25395, Pacific Northwest National Laboratory, May 2016.
[13] Berndt, Franke, and Mortreau, "^{235}U Enrichment or UF_6 Mass Determination on UF_6 Cylinders with Non-Destructive Analysis Methods," 316.
[14] Ibid., 312–313.
[15] This assumption is also used in Walker and Goldston, "Timely Verification at Large-Scale Gas Centrifuge Enrichment Plants."
[16] "SWX-237 High Temperature Boron-Silicone Neutron Shielding," Shieldwerx, Revised November 2015, http://www.shieldwerx.com/assets/swx-237.pdf.