Nuclear Non-Proliferation Regime Effectiveness: An Integrated Methodology for Analyzing Highly Enriched Uranium Production Scenarios at Gas Centrifuge Enrichment Plants

by

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Abstract

The dramatic change in the international security environment after the collapse of the bipolar system has had a negative impact on the effectiveness of the existing nuclear non-proliferation regime. Furthermore, the success of the Pakistani Gas Centrifuge Enrichment Technology (GCET)-based nuclear weapons program has imposed a great challenge on the Nuclear Nonproliferation Treaty (NPT) regime. In this context, this study tried to answer two questions: (a) what is the probability of proliferators successfully producing Highly Enriched Uranium (HEU) at Gas Centrifuge Enrichment Plants (GCEPs) and (b) how effective is the current NPT regime in dealing with this issue.

In order to tackle these two questions, an integrated methodology is used that reflects all factors affecting the nuclear proliferation on the front-end of the nuclear fuel cycle. A quantitative assessment of the proliferation risks of producing HEU for multiple scenarios is presented using success tree models, uncertainty analysis, sensitivity analysis, importance measures, and expert opinion. This assessment identifies the factors that can reduce the proliferators' success of producing HEU, which will be helpful in prioritizing the use of the IAEA's limited resources.

The study found that legal capabilities of the NPT regime are more problematic than technological capabilities in preventing proliferators from producing HEU at GCEPs, since the United Nations Security Council (UNSC) is the only NPT regime component that has compliance-enforcing resources. This study recommends three approaches as follows: First, the NPT regime should take a multi-faceted approach that incorporates all NPT regime components into each step of nuclear weapons program development. Second, the NPT regime should impose nuclear elements control via Multilateral Export Control Regimes (MECRs). Third, the NPT regime should develop an approach that challenges HEU production from both technological- and legal points of view. Since law governs technological capability, a multidimensional approach that includes this relationship would be more effective than an approach that focuses on either aspect individually.

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Acronyms

AP	Additional Protocol
ATTA	Atom Trap Trace Analysis
AVLIS	Atomic Vapor Laser Isotope Separation
BE	Basic Event
BOG	Board of Governors
CA	Complementary Access
CDF	Cumulative Distribution Function
CEMO	Continuous Enrichment Monitoring System
CHEM	Cascade Header Enrichment Monitor
CSA	Comprehensive Safeguards Agreement
C/S	Containment and Surveillance System
CSI	Commercial Satellite Imagery
COK	Continuity of Knowledge
CPPNM	Convention on the Physical Protection of Nuclear Material
CTBT	Comprehensive Test Ban Treaty
DA	Destructive Assay
DIAL	Differential Absorption LIDAR
DIV	Design Information Verification
ESWA	Environmental Sampling over Wide Area
FFP	Fuel Fabrication Plant
FMCT	Fissile Material Curt-off Treaty
GCEP	Gas Centrifuge Enrichment Plant
GCET	Gas Centrifuge Enrichment Technology
GDP	Gaseous Diffusion Plant
HEU	Highly Enriched Uranium
HPTA	High Precision Trace Analysis
HSP	Hexapartite Safeguards Project
HUMINT	Human Intelligence
IAEA	International Atomic Energy Agency
IFOV	Instant Field of View
IIV	Interim Inventory Verification
ITDB	Illicit Trafficking Database
LCBS	Load Cell Based Weighing System
LEU	Low Enriched Uranium
LFUA	Limited Frequency Unannounced Access
LIDAR	Light Detection and Ranging
LWR	Light Water Reactor
MECR	Multilateral Export Control Regime
MMSP	Multi-Member States Support Program
MLIS	Molecular Laser Isotope Separation

MPS	Minimal Path Set
MUF	Material Unaccounted For
NDA	Non-Destructive Assay
NNWS	Non-Nuclear Weapon States
NWS	Nuclear Weapon States
NPT	Treaty on the Non-proliferation of Nuclear Weapons or Nuclear Nonproliferation Treaty
NRFI	Nuclear Resonance Fluorescence Imagery
NSG	Nuclear Suppliers Group
NTM	National Technical Means
NU	Natural Uranium
NWAL	Network of Analytical Laboratories
NWFZ	Nuclear Weapon Free Zone
PIV	Physical Inventory Verification
PR	Proliferation Resistance
PRF	Plutonium Reprocessing Facility
PSI	Proliferation Security Initiative
PSP	Proliferator Success Probability
RTD	Relative Temperature Difference
SAL	Safeguards Analysis Laboratory
SDS	Surface Deposition Sampling
SIAL	Satellite Imagery Analysis Unit
SNRI	Short Notice Random Inspection
SQ	Significant Quantity
SSAC	State System of Accounting for and Control of Nuclear Material
SWU	Separative Work Unit
TCP	Temporary Complementary Protocol
TDLS	Tunable Diode Laser Spectrometry
TIR	Thermal Infrared
TTA	Nuclear Trade and Technology Analysis Unit
UCF	Uranium Conversion Plant
UER	Uranium Enrichment Ratio
UNARM	Unattended and Remote Monitoring System
UNSC	United Nations Security Council
VNIR	Visible and Near-Infrared
VRS	Voluntary Reporting Scheme
WA	Wassenaar Arrangement
WAES	Wide Area Environmental Sampling
WGU	Weapons-Grade Uranium
WGPu	Weapons-Grade Plutonium
XRF	X-ray Fluorescence
ZC	Zangger Committee

INTRODUCTION TO STUDY

CHAPTER 1 INTRODUCTION

1.1 Background

Since the enforcement of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) in 1970, only India and Israel successfully detonated nuclear bombs in the decade that followed. After the demise of the Soviet Union and collapse of the bipolar system, the resulting dramatic change in the international security environment negatively impacted the non-proliferation regime. As a result, North Korea, Pakistan, Iran, Syria, Iraq and Libya attempted to acquire nuclear weapons, with North Korea and Pakistan doing so successfully. At the time, the international community considered these countries incapable of developing nuclear weapons programs. These countries' success, contrary to public belief, implies that nuclear weapons technology had spread to states of very limited resources and technology.

The international community has continued its efforts to build a more effective non-proliferation regime in response to this threat. A number of frameworks have been proposed to deal with nuclear proliferation issues. These frameworks are known as the nuclear non-proliferation regime or the NPT regime, named after the original NPT mentioned previously. These efforts seemed to be successful until Pakistan and North Korea conducted nuclear weapons testing in 1997 and 2006, respectively. This implies that the NPT regime may have not been effective in nuclear nonproliferation. Furthermore, the emergence of nuclear black markets, so-called A. Q. Khan Network, has been imposing a serious challenge to the NPT regime because the network enabled the clandestine uranium enrichment program of Libya and Iran with the Pakistan's Gas Centrifuge Enrichment Technology (GCET).

Unfortunately, the International Atomic Energy Agency (IAEA) and other intelligence agencies did not detect nuclear weapons in these countries until Iran and North Korea reached the final stage of development. In addition to the decreased stability of international order, the spread of dual-use technologies with potential Weapons of Mass Destruction (WMD) applications has also contributed to the proliferation of nuclear weapons. Therefore, the international community is questioning the effectiveness of the current NPT regime in addressing and resolving non-proliferation challenges.

Methods of strengthening the NPT regime have been continuously researched over the last several decades. However, most of the studies have limitations in connecting theories to practice. First, most studies have limited scopes in analyzing nuclear proliferation, focusing on only a few details of the entire problem. Second, most studies suggest only hypothetical solutions to solving non-proliferation issues. Therefore, further research is required in order to improve the manner by which the NPT regime prevents and disables nuclear proliferation especially using GCET.

1.2 Thesis Objectives

Non-proliferation of nuclear weapons is inherently an issue of international politics. Like other international regimes, the NPT regime has both political or legal and technological means to achieve its objective. These two means should complement each other.[1] However, due to the unique nature of nuclear technology, the emphasis placed on technological means should be greater than those of any other international regimes. The technological means of the NPT regime can be represented by the IAEA safeguards; however, the implementation of IAEA safeguards requires political means. In this regard, it would be correct to define the IAEA safeguards as the combination of legal and technological means.

In order to evaluate the capabilities of the NPT regime, particularly in dealing with the nuclear proliferation based on GCET, it is essential to develop a methodology that systematically diagnoses the NPT regime. The clear understanding of capabilities and limitations of the NPT regime is the backbone to solve complex nuclear non-proliferation issues. Therefore, the objectives of this thesis are as follows:

Objective I: To develop a risk analysis model for Highly Enriched Uranium (HEU) production at Gas Centrifuge Enrichment Plants (GCEPs)

- What are the capabilities of proliferators for producing HEU at GCEPs?
- What are the capabilities of the NPT regime?
- What is the probability of proliferators successfully producing HEU at GCEPs?

Objective II: To make recommendations for the NPT regime to reduce the risks associated with GCEPs

- What problems hinder the effectiveness of the NPT regime?
- What will increase the effectiveness of the current NPT regime?

1.3 Previous Work on Nuclear Non-proliferation

Previous non-proliferation studies have been performed from either a political or engineering perspective. It is important to recognize that the combination of these two perspectives would result in more robust non-proliferation policies against nuclear proliferation. However, a study that embraces all components of the NPT regime and both legal and technological perspectives has not been performed.

[1] Ryukichi Imai, "Safeguards against Diversion of Nuclear Material: An Overview," *Annals of American Academy of Political and Social Science (AAPSS)* 430 (March 1977).Imai provides a good discussion about the different positions and roles between the politicians and the technological community for nonproliferation. He claims that it is important to accept the definite limitations of the capabilities of the IAEA safeguards. Then the combination of safeguards and political tools will effectively work for nonproliferation.

1.3.1 Types of Non-proliferation Studies

Figure 1.1 shows types of non-proliferation studies. These studies are typically divided into two approaches: Nuclear Engineering and Political Science. From a political approach, studies generally focus on why and how a governing body makes the decision to "go-nuclear". Engineering-based research analyzes diversion scenarios during the nuclear fuel cycle process and the effectiveness of safeguard systems.

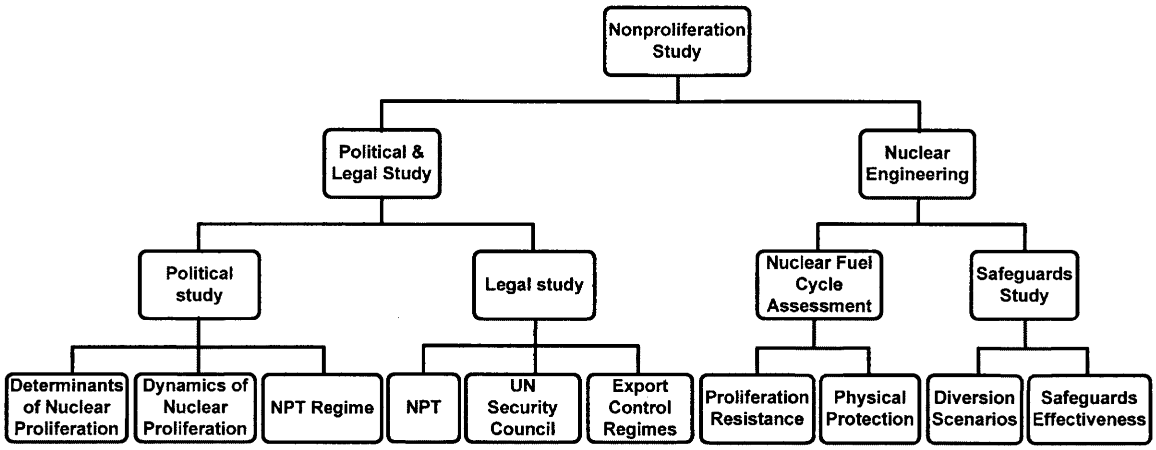

Figure 1.1 Types of Nonproliferation Study

1.3.2. Previous Nuclear Proliferation Research from Political and Legal Standpoints

Finding determinants of a state's decision to support nuclear proliferation has been a popular topic in political science-based studies. Stephen Meyer (1984) studied a model that analyzed ***nuclear propensity*** over time by considering technological capabilities and the relative presence or absence of motivation variables. Other research has analyzed the relationship between economic and technological capabilities of countries and their propensity on nuclear proliferation. Legal-based studies concerning nuclear nonproliferation generally review the legal effectiveness of the NPT, United Nations Security Council (UNSC), and export control regimes.

1.3.3. Previous Nuclear Proliferation Engineering-Based Research

A. Proliferation Resistance Evaluation

Proliferation Resistance (PR) is defined as the characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material or misuse of technology in order to acquire nuclear weapons or other nuclear explosive device.[2] A nuclear energy system that has a high PR will decrease the probability of nuclear proliferation of nuclear weapons.[3] This is due to the fact that such facilities are difficult to divert for military purposes. The US Department of Energy (DOE)' TOPS (1),[4] Generation IV International Forum (GIF)'s PR & PP evaluation (2006),[5] IAEA's INPRO (2007),[6] and William Charlton et al. (2006)'s Multi-attribute Utility Analysis (MAUA)-based study[7] provide good examples of such facilities.

B. Safeguards Modeling

Safeguard studies includes diversion scenario analysis and modeling of safeguard effectiveness based on developed scenarios. Los Alamos National Laboratory (LANL) (1995) conducted a safeguard options study that provided proliferation pathways (diversion scenarios and methods), objectives of enhanced safeguards, needs for enhanced safeguards, and options enhanced safeguards for an entire fuel cycle.[8]

Lawrence Livermore National Laboratory (LLNL) has been modeling nuclear safeguard effectiveness for uranium-treating facilities using *LLNL Integrated Safeguards System Analysis Tool* (LISSAT). LISSAT can be used as a framework that can perform systems analysis for evaluating the effectiveness of a safeguard system for a nuclear fuel cycle facility.[9] Modeling efforts using LISSAT were made for the safeguard approaches to Uranium Conversion Facilities (UCFs) and GCEPs. H. Elayat et al., (2004) analyzed safeguard effectiveness in a UCF and a GCEP and developed diversion scenarios such as the "skimming scenario."[10] Later, H. Lambert et al., (2007) evaluated and compared effectiveness of different safeguard options to GCEPs.[11]

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[2] IAEA, *Proliferation Resistance Fundamentals for Future Nuclear Energy Systems* (IAEA, STR-332,, December 2002).

[3] Matthew Bunn, *Proliferation-Resistance (and Terror Resistance) of Nuclear Energy Systems: Harvard University Lecture for Nuclear Energy Economics and Policy Analysis* (Harvard University, April 12, 2004); available from http://ocw.mit.edu/NR/rdonlyres/Nuclear-Engineering/22-812JSpring2004/0B02F941-0668-4952-A209-E9A160766B33/0/lec17slides.pdf.

[4] Task Force on the Nuclear Energy Research Advisory Committee U.S. Department of Energy, "Technical Opportunities for Increasing the Proliferation Resistance of Global Civilian Nuclear Power System (TOPS) " (Oct. 2000).

[5] GIF/PRPPWG-2006/005, "Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems," (November 2006).

[6] IAEA, "Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy System: INPRO Manual-Overview of the Methodology," (IAEA-TECDOC-CD-1575 Rev.1, Nov. 2008).

[7] William S. Charlton et al., "Proliferation Resistance Assessment Methodology for Nuclear Fuel Cycles," *Nuclear Technology*, no. 157 (Feb. 2007).

[8] E.A. Hakkila et al., *The Safeguards Options Study, LA-12918-MS* (Los Alamos, NM: Los Alamos National Laboratory, April 1995).

[9] W.J. O'Connell H.A. Elayat, and B.D. Boyer, "Gas Centrifuge Enrichment Plant Safeguards System Modeling" (paper presented at the Proceedings of the 45th Annual Conference of the Institute of Nuclear Materials Management INMM, Nashville, TN, July 16-20, 2006).

[10] H. A. Elayat, Howard Lambert, and William J. O'Connell, "Systems Analysis of Safeguards Effectiveness in a Uranium Conversion Facility" (paper presented at the Proceedings of the 45th Annual Conference of the Institute of Nuclear Materials Management INMM, Orlando, FL, July 10-14, 2004), H.A. Elayat, "Gas Centrifuge

C. HEU Production Scenarios

Table 1.1 summarizes previous studies about proliferation scenarios for producing HEU at GCEPs with results and limitations. The Safeguards Options Study (1995) conducted by Los Alamos National Laboratory provides an extensive analysis of different scenarios to produce HEU at Uranium Enrichment Facilities (UEFs).

Table 1.1 Comparison of Studies on HEU Production Scenarios

Study	Scenarios studied	Results / Limitations
Safeguards Options Study (1995)	**Sneak-out and Break-out scenarios** (1) Unauthorized activities at declared facilities • Different off-design operation modes (2) Undeclared uranium enrichment facilities	**Results** • Quantitative comparison for various off-design operation modes, including timelines
IISS (2005)	**Sneak-out and Break-out scenarios** (1) Break-out • Different SWU capacities • Different feeds (NU, 5% LEU) • Different tails assay (0.4 and 2 %) (2) Sneak-out • Clandestine GCEP with clandestine UCF • Concurrent use of a declared and clandestine GCEP	**Results** • Theoretical operating time to produce 25 kg of 93% HEU **Limitation** • No data on total required masses • No quantitative analysis on sneak-out scenario
Alexander Glaser (2008)	**Break-out scenario** in two modes of operation with different feeds (1) Approaches • Batch recycling and cascade interconnection (2) Feeds and SWU requirement • NU feed with 6,000 P-1 machines • 3.5 % LEU feed with 2,000 P-1 machines	**Results** • Production rate (kg per year) • SWU requirements
Gregory Jones (2008)	**Sneak-out and Break-out scenarios** (1) Clandestine GCEP • NU feed • 4.8 % LEU feed (2) Batch recycling at declared GCEP • Various SWU capacity expansion scenarios (from 7,500~75,000 SWU/yr)	**Results** • Required time to produce 20 kg of 93.1% HEU

1.4 Scope of Work

Nuclear non-proliferation is basically a political objective. However, it is necessary to understand the technological aspect of nuclear proliferation if this problem is to be solved. Thus, nuclear non-proliferation should be understood from both an engineering and political standpoint. Figure 1.2 shows the topology of topics explored in this study.

Enrichment Plant Safeguards System Modeling".; and H.A. Elayat, "Gas Centrifuge Enrichment Plant Safeguards System Modeling".

[11] H. Elayat H. Lambert, W. J. O'Connell, L. Szytel, M. Dreicer, "LISSAT Analysis of a Generic Enrichment Plant" (paper presented at the 48th Annual Meeting of the Institute Nuclear Materials Management Tucson, AZ, July 2007).

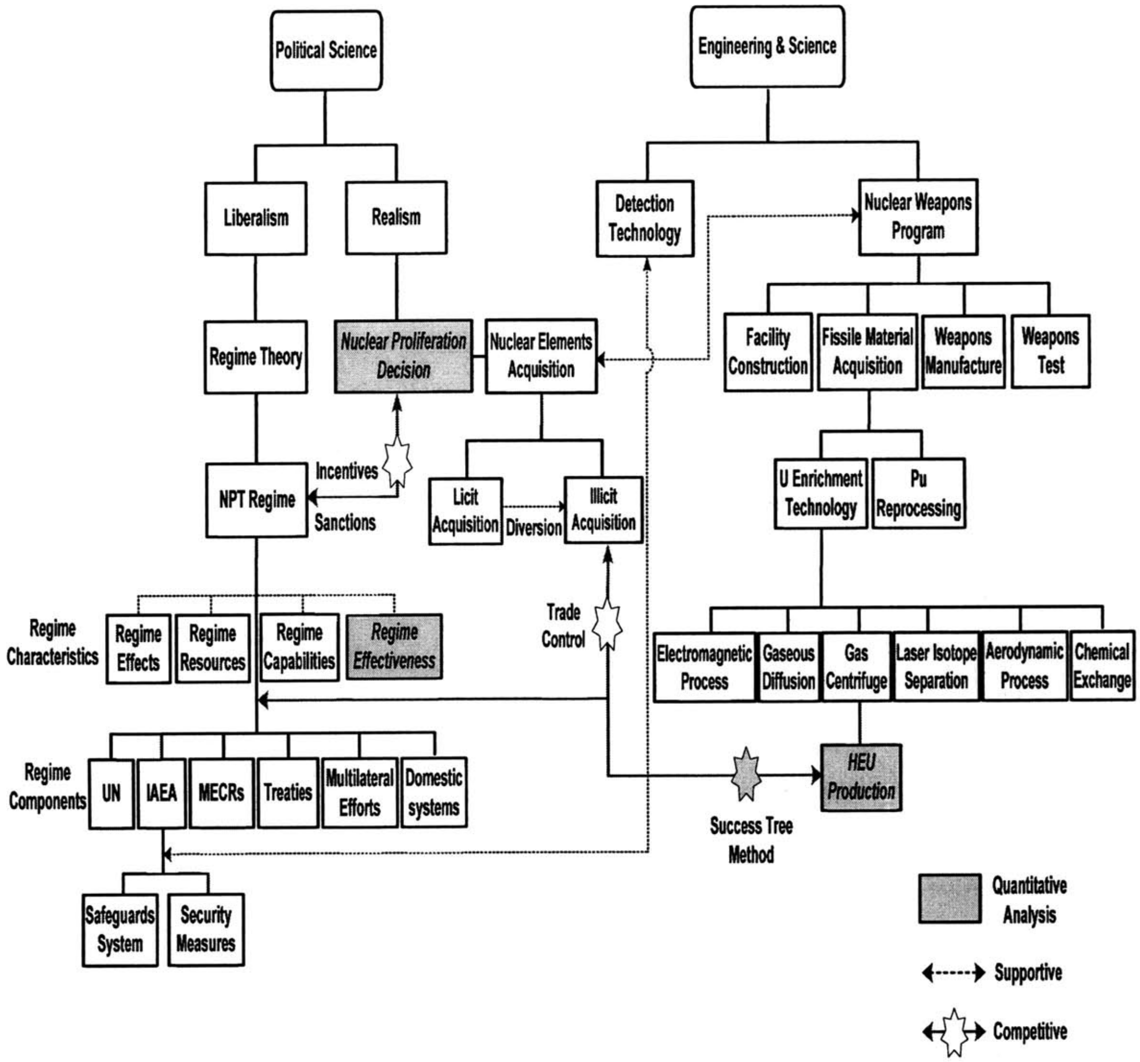

Figure 1.2 Topology of Study

In political science, the dynamics of nuclear proliferation and the analysis of the NPT regime using regime theory are the main topics. Analyzing the capabilities of the NPT regime components including the IAEA, the United Nations (UN), Multilateral Export Control Regimes (MECRs), treaties, and the Proliferation Security Initiative (PSI) is the basis of understanding of what can be done to prevent nuclear proliferation by the international community. In this case, each element has its own unique features and capabilities in preventing nuclear proliferation.

In the area of engineering and science, the technological analysis of nuclear weapons programs and the NPT regime's technological capabilities for detecting or verifying[12] nuclear weapons programs

[12] In engineering or a quality management system, "verification" is the act of reviewing, inspecting, testing, etc. to establish and document that a product, service, or system meets the regulatory, standard, or specification requirements. Detection is the extraction of information from any clear or clouded ambient or otherwise accessible stream of information without neither support from the sender nor synchronization to the sender.

are important issues. Among various technologies required for a nuclear weapons program the acquisition of fissile materials, Highly Enriched Uranium (HEU) and Weapon-Grade Plutonium (WGPu), is the most important and difficult step. Recent studies have also found that Gas Centrifuge Enrichment Technology (GCET), used in the production of HEU, imposes the most serious threat to the NPT regime. Thus, the success probability of clandestine HEU production was chosen for a quantitative study. The areas included in the present study are listed in Table 1.2.

Table 1.2 Areas of Study

Areas of study	Topics
Political and legal science	• Incentives and disincentives for nuclear proliferation • Regime theory • Legal authority and effects of international arrangements
Nuclear engineering and science	• Nuclear weapons program and nuclear fuel cycle - Uranium conversion technology - Uranium enrichment technology
Generic engineering	• Technological background of nuclear weapons program detection - Satellite imagery -Destructive assay and nondestructive assay
Quantitative analysis	• Success tree methods for risk analysis
IAEA safeguards	• Field experience regarding the actual application of IAEA's safeguards

1.5 Methodology

The procedure developed for evaluating the success probability of HEU production is based on the methodology developed by Ham (2004).[13] He called his procedure an "***integrated methodology***"[14] since it fully characterized all elements of nuclear proliferation - from the definition of actors, to quantitative pathway analysis via the export elicitation. In the present study, the methodology developed here is also considered an integrated methodology but differs from Ham's definition in the following contexts:

• Integration of legal and engineering aspects

Compare both legal and technological measures in the NPT regime against nuclear proliferation activities

[13] Hyeongpil Ham, "An Integrated Methodology for Quantitative Assessment of Proliferation Resistance of Advanced Nuclear Systems Using Probabilistic Methods" (MIT, June 2005). Chapter 2.

[14] PNNL defines an integrated methodology as "a set of computer tools that have been interfaced to enable the undertaking of a complete nonproliferation assessment." S. V. Mladineo et al., "Guidelines for the Performance of Nonproliferation Assessments," (Pacific Northwest National Laboratory (PNNL), PNNL-14294, May 2003).

• **Integration of various quantitative methods**

Probabilistic Risk Assessment (PRA) using success trees, expert elicitation, and quantitative analyses. [15]

• **Integration of field experience and theoretical studies**

Combining experiences from IAEA inspections and theoretical backgrounds including inspection technology such as satellite imagery

• **Integration of all components in a typical nuclear fuel cycle**

1.6 Results of Study

1.6.1 NPT Regime Study

A. Dynamics of Nuclear Proliferation

The dynamics of nuclear proliferation are so complex because there are many factors that govern its existence. Under particular situations, some of these factors are competing. These factors can be classified into the following three categories:

- Environment: international (exogenous) and domestic (endogenous)
- Features: political, military and economic,
- Duration: fixed and situational

Causal loop diagrams, one of the important tools of system dynamics, were chosen in order to describe the complexity of nuclear proliferation dynamics.[16] Two diagrams were chosen in order to describe nuclear dynamics from two different dimensions: (a) a domestic level focusing on endogenous variables, and (b) an international level focusing on exogenous variables.

B. The NPT Regime's Safeguard Effectiveness

Three approaches to evaluate the power and effectiveness of the NPT regime were proposed. To evaluate the effectiveness of the NPT regime, the number of states that acquired nuclear weapons during specific time periods was calculated. This study found that the NPT regime has been previously effective, but is currently facing challenges because of the instability in the international security environment and the spread of nuclear weapons technology.

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[15] Ibid., Chapter 9. Assessment Methods and Tools, pp.42-85.

[16] System dynamics is an approach to understanding the behavior of complex systems over time. What makes using system dynamics different from other approaches to studying complex systems is the use of feedback loops and stocks and flows. These elements help describe systems with a variety of affecting factors to a system. In particular, causal loop diagrams are useful in describing causes and results in the form of feedback. John D. Sterman, *Business Dynamics: Systems Thinking and Modeling for a Complex World* (Boston, MA: McGraw-Hill Higher Education, 2000). ,pp.141-149.

C. The NPT Regime's Power

The NPT regime's power can be described qualitatively using selected evaluation criteria: resources and capabilities. These criteria are described as follows:

- Resources: Implementing, compliance-enforcing, and verifying resources
- Capabilities: legal and technological capabilities

The power of all NPT regime components was analyzed in terms of these two basic qualitative evaluation criteria.

1.6.2 HEU Production at GCEPs

A. Scenario Development and Modeling

Three scenarios for producing HEU at GCEPs were identified through a literature survey: (a) a break-out scenario using a declared GCEP, (b) a sneak-out scenario using a clandestine GCEP only, and (c) a concurrent sneak-out scenario using both a clandestine and a declared GCEP. All three of these scenarios are composed of two main strands: the provision of nuclear material to a GCEP and the off-design or clandestine operation of a GCEP for HEU production. Detailed descriptions of these scenarios are available in Table 1.3.

Table 1.3 Topology of Success Trees for HEU Production Scenarios

Basic Events Categorization	Proliferation activities to detect
HEU production in off-design operation modes	[1] HEU production in batch recycling mode [2] HEU production in reconfiguration mode [3] HEU production with Add-on modular cascades [4] HEU production in connection of multiple cascades
Excess LEU production in undeclared operation modes	[5] Excess LEU production for additional time [6] Excess LEU production at increased product rate [7] Excess LEU production with add-on cascades
Diversion of nuclear material from a nuclear fuel cycle	[8] Diversion from Light Water Reactors (LWRs) [9] Diversion from Uranium Conversion Facilities (UCFs) [10] Diversion from Fuel Fabrication Plants (FFPs) [11-12] Diversion from GCEPs: NUF6 , LEUF6
Operation of declared UCFs for processing undeclared uranium	[13] Conversion of NU to NUF6 [14] Conversion of LEU to LEUF6
Detection of clandestine UCF / GCEP	[15-18] ESWA/LIDAR/DIAL at short distances /at long distances for both clandestine GCEPs and UCFs. [a] [19-20] Commercial satellite imagery and military satellite imagery for clandestine GCEPs.
Illicit acquisition of nuclear material	[21] NU, [22] NUF6, [23] LEU, [24] LEUF6

Note: [a] ESWA (Environmental Sampling over Wide Area), LIDAR (Light Detection and Ranging), and DIAL (Differential Absorption LIDAR)

B. Summary of Experts Opinion

Table 1.4 presents a qualitative summary for each basic event as evaluated by experts in each field. Quantitatively-evaluated values were used as input for calculating success probabilities using the success trees developed in this study. From this table, it is evident that the detection of clandestine operation of GCEPs and UCFs is highly unlikely. However, the detection of clandestine UCFs is more promising than clandestine GCEPs for detecting nuclear weapons.

Table 1.4 Evaluation of Proliferator Success Probability from Experts

Cases		Safeguarders' possible detection means	Evaluation on proliferator success probability
Declared GCEP operation	Excess LEU production	Safeguards	Likely
	HEU production		Unlikely – likely
Declared UCF operation	Undeclared NU	Safeguards	Highly likely
	Undeclared LEU		Unlikely-likely
Declared uranium diversion	UF6 from UCFs, GCEPs	Safeguards	Likely
	Non-UF6 from Reactors, FFPs	Safeguards	Highly likely
Undeclared uranium illicit acquisition	UF6 form (NU/LEU)	Safeguards	Likely-highly likely
	Non-UF6 form (NUF6/LEUF6)	Safeguards	Highly likely
Clandestine GCEP operation	HEU production	Environmental sampling	Highly likely
		DIAL	Highly likely
		Satellite imagery	Highly likely
Clandestine UCF operation	Undeclared NU/LEU	Environmental sampling/ LIDAR	Likely-highly likely

Notes
[a] LIDAR (Light and Detection Ranging) and DIAL (Differential Absorption LIDAR)
[b] Highly likely (75-100%), likely (50-75%), unlikely (25-50%), and highly unlikely (0-25%).

C. Summary of Quantitative Results

Two types of quantitative evaluation were performed using the success trees developed in this study. First, proliferators' success probabilities were analyzed for two types of countries (countries under INFCIRC/153 and those under INFCIRC/540) given Scenarios (a), (b), and (c). The purpose of this analysis was to examine the difference in probabilities for countries with high levels of IAEA safeguard applications and compliance vs. countries with low levels. The results showed that the probability of successfully producing HEU would be significantly high, if a proliferator decided to do so. Additionally, three types of quantitative analyses including uncertainty analysis, sensitivity analysis, and importance analysis were performed. These analyses demonstrated that the success tree models were very useful in identifying strengths and weaknesses of the NPT regime and exploring the impacts of possible policy implications. However, they are subject to a high level of uncertainty. For this reason, additional research would help in strengthening the conclusions presented in this study.

1.7 Thesis Organization

This study is composed of four parts as shown in Figure 1.3. Part I is an introduction to the study and an overview of an integrated methodology. Part I and II contain two main themes of the study. Part I is dedicated to identifying features and capabilities of two actors, the NPT regime and proliferators, competing in the Nuclear Nonproliferation Treaty (NPT) regime. Safeguarders are the ones in charge of preventing proliferators from developing their nuclear weapons programs. Part I is essential to understanding the complex problems of nuclear proliferation that the international community is facing. To that end, Part I includes the followings; a review on political theories about why and in what cases states want to have nuclear weapons (Chapter 3); a general description about a nuclear weapons program (Chapter 4); generic capabilities of the NPT regime (Chapters 5) and features and capabilities of the IAEA, as sole NPT components with verification resources (Chapter 6 and 7). Part I works as a framework to formulate the capabilities of the NPT regime, which are necessary to the integrated methodology developed in Part II.

Part II focuses on the quantitative evaluation of success probabilities of proliferators in producing HEU through an integrated methodology. Part II contains four parts: (a) technological analysis on uranium enrichment technology and gas centrifuge enrichment technology (Chapters 8 and 9); (b) legal and technological analysis on the IAEA's capabilities for preventing HEU production at GCEPs (Chapters 10 and 11); (c) development of proliferators' scenarios for producing HEU (Chapters 12 and 13); and (d) modeling of HEU production scenarios and a quantitative analysis of the model through an integrated methodology. (Chapter 14) Finally, the conclusion of the study provides the summary of the study and provides recommendations to strengthen the current NPT regime.

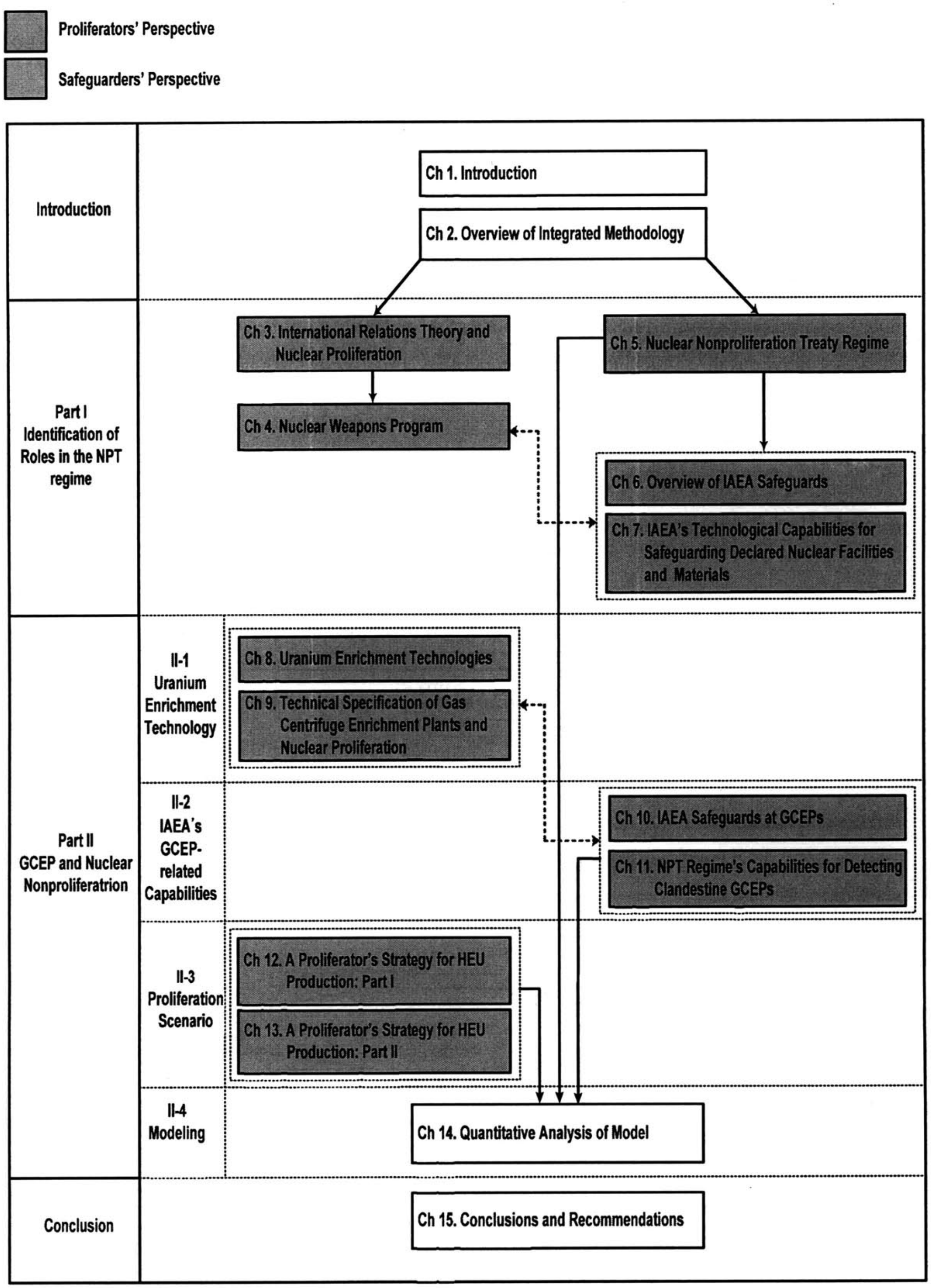

Figure 1.3 Composition of Chapters

CHAPTER 2

OVERVIEW OF AN INTEGRATED METHODOLOGY

2.1 Introduction – Modeling Procedure and Integrated Methodology

This chapter is devoted to the brief description of a general procedure to conduct the integrated methodology developed for evaluating success probabilities of Highly Enriched Uranium (HEU) production. This integrated methodology evaluates probabilities using success tree analysis. This modeling procedure starts with problem identification and ends with quantitative analysis of the model. The quantitative results of this integrated methodology are provided in Chapter 14.

2.2 Modeling Procedure

The integrated methodology developed in this study is performed in eight steps from problem identification to quantitative analyses as shown in Figure 2.1.

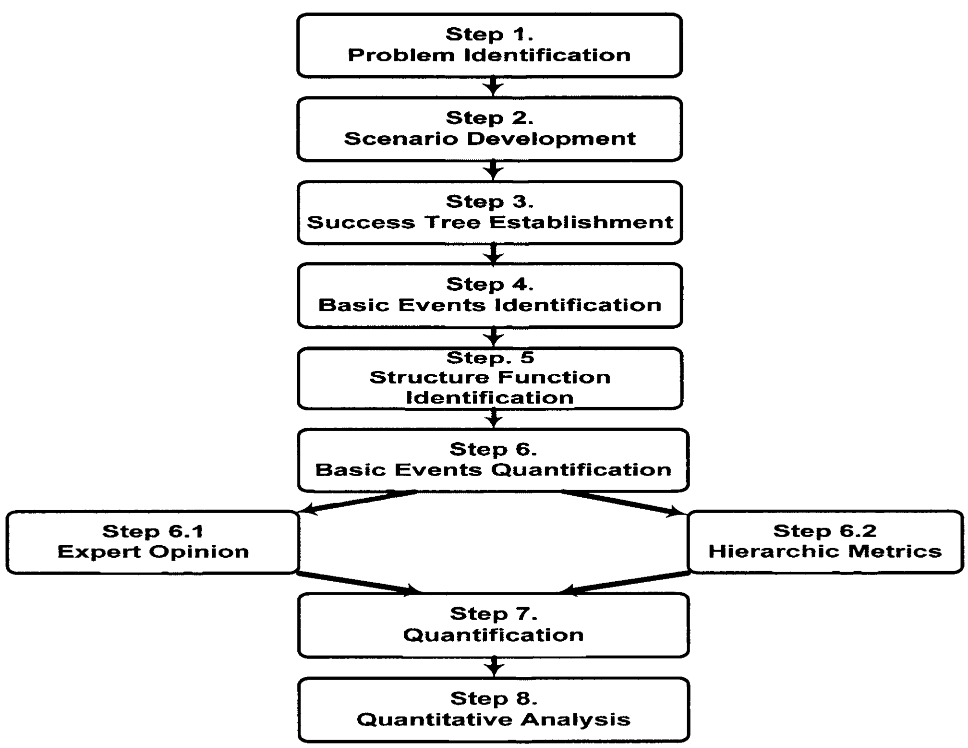

Figure 2.1 Procedures for Developing Integrated Methodology

The first step is to identify the problem that modelers are interested in. For this step, modelers need an extensive survey to develop an understanding of the problem, which will be the fundamental background of the model-building process. The second step is to identify and develop plausible scenarios that describe how two actors, safeguarders and proliferators in this study, will interact. This is essential because nuclear proliferation involves the competition between safeguarders and proliferators. This step requires field experience and creativity to develop realistic scenarios.

The third step is to build success trees based on the scenarios developed in step two. The establishment of success trees translates narrative scenarios into a logical flow of sequential events. The goal of establishing success trees is to obtain quantified probability values for the overall questions of proliferation, otherwise known as 'top events'. This quantification process involves the identification of a structure function (step 5) and the evaluation of basic events (step 4 and 6). The last step is to conduct quantitative analyses to develop insights based on different model settings used to simulate a variety of environments. Generic tasks and specified tasks for each step are described in Table 2.1.

Table 2.1 Procedure to Perform an Integrated Methodology

Step		Generic tasks	Specified tasks (nonproliferation)	Relevant Chapters
1	**Problem identification**	Introduction to problem	What are the characteristics of a Nuclear Weapons Programs? What is the Nuclear Nonproliferation Regime?	4,5
		Interacting players identification	Features of proliferators and safeguarders -Who are they? -What can they do?	3,5, 6,7
2	**Scenario development**	Target identification	What are elements required for nuclear weapons programs?	8,9
		Safeguarder's strategy identification	How do safeguarders prevent nuclear weapons programs?	10, 11
		Proliferator's strategy identification	How do proliferators pursue a nuclear weapons program?	12, 13
		End state definition	What is the end state and how is it defined?	14
3	**Success tree establishment**	Build success trees using events and logical gates	Translate proliferation scenario into success trees	14
4	**Basic events identification**	Identification of basic events	Grouping of basic events	14
5	**Structure function**	Identification of system functions	Equation for calculating top events probability	14
6	**Basic events evaluation**	Quantification of basic events	Expert opinions elicitation through questionnaire Top metrics development	14
7	**Quantification**	Quantification of models	Top events probabilities calculation using Saphire	14
8	**Quantitative analysis**	Uncertainty analysis Sensitivity analysis Importance analysis	Explore various policy options and technology levels	14

2.3 Step 1. Identification of the Problem

The first step in any model development involves the understanding of the problem. In the present study, a nuclear proliferation world is defined as the arena where the two actors, safeguarders and proliferators, are interacting with regard to nuclear weapons program-related technology, materials and equipment as shown in Figure 2.2. The characterization of actors and nuclear weapons programs is the basic step towards building a model that describes nuclear proliferation problems.

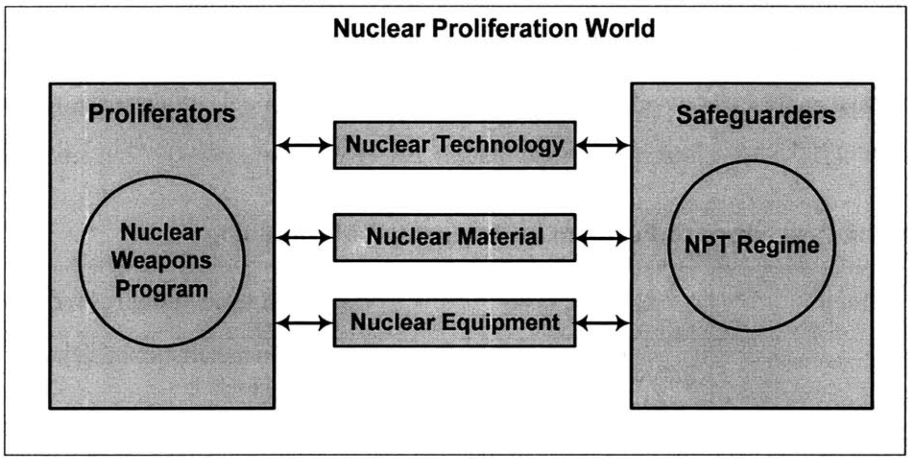

Figure 2.2 Schematic Drawing of Nuclear Nonproliferation System

In the nuclear proliferation world, the two actors are competing with each other for control of nuclear elements. Nuclear elements are defined as components required for a nuclear weapons program such as nuclear technology, nuclear material, and nuclear equipment.

Proliferators want to develop nuclear weapons and their schemes for acquiring nuclear weapons are represented by nuclear weapons program. The following assumptions are made with regard to the characteristics of proliferators:

- **Assumption #1**: Potential proliferators include only state actors, not non-state actors.
- **Assumption #2**: Every country has a will to develop nuclear weapons if they are allowed to. At a minimum, they are ready to consider an option to acquire nuclear weapons.
- **Assumption #3**: Potential proliferators can divert material from a nuclear fuel cycle into a nuclear weapons program.
- **Assumption #4**: Proliferators continue to try to look at the vulnerabilities of the safeguarder itself or safeguard measures and obtain useful information in order to improve their diversion or concealment tactics.

Safeguarders want to prevent or stop the proliferation of nuclear weapons. Safeguarders' actions against nuclear proliferation are performed through the authorization of the nuclear nonproliferation regime. In this study, safeguaders are defined as actors within the NPT regime, and are generally represented by the IAEA.

2.4 Step 2. Scenario Development

The scenarios used in this study will cover the interactions between proliferators and safeguarders. To fully develop realistic scenarios, the strategies of both the proliferators and the safeguarders must be considered. In order to apply our methodology we will focus our scenarios on one aspect of a Nuclear Weapons Program, the procurement of fissile material.

2.4.1 Nuclear Weapons Program

A nuclear weapons program begins with the decision to initiate pursuit of nuclear weapons and is complete upon the test of a manufactured nuclear device. A nuclear weapons program requires an extensive range of technologies and resources. By looking at overall nuclear weapons program, required technology, material, and equipment for the successful completion of nuclear weapons programs can be identified. The process of developing nuclear weapons involves many steps. The most difficult and critical step is the procurement or production of highly enriched uranium (HEU).

2.4.2 HEU production

In this study, the step of fissile material acquisition was chosen for a quantitative analysis using success tree techniques due to its importance and complexity. HEU production can be conducted at two types of Uranium Enrichment Facilities (UEFs): declared and clandestine facilities. In some cases, it is even possible to use two types of facilities simultaneously. For the successful production of HEU, proliferators need to prepare nuclear material, and build or buy specialized equipment and technology.

2.5 Step 3. Success Tree Development

A success tree using a logic diagram provides a systematic approach to the incorporation of all root causes (basic events) for each *proliferation scenario.* The main purpose of a success tree method is to translate identified scenarios and root causes that lead to the top event in a clear, systemic fashion into a format that allows quantitative analysis. A success tree method also helps identify diversion scenarios that were not identified in step two. Each step of a nuclear weapons program can be analyzed with the integrated methodology; however, only HEU production is analyzed in this study. Before starting success tree development, several factors are considered. First, developers should define the top events, depending on the purposes of study or based on the ease of quantification as shown in Table 2.2.

Table 2.2 Possible Ways to Build Success Trees or Failure Trees

Actors	Results	Name	Possible description of a top event
Safeguarders	Success	A	A nuclear weapons program is successfully stopped.
	Failure	B	A nuclear weapons program is not detected. A nuclear weapons program is not stopped.
Proliferators	Success	C	A nuclear weapons program is successfully completed.
	Failure	D	A nuclear weapons program failed. A nuclear weapons program is detected.

Second, the level of detail for describing basic events should be defined. A success tree can be built either in a very complex, detailed way or in a very simple, rough manner. The advantage of simple success trees is that they are easily understood, but by simplifying the tree it becomes more difficult to accurately quantify the probabilities. The resulting calculations may not provide the level of detail that is necessary to describe the probability of the top event.

2.6 Step 4. Basic Events Identification

In the process of success tree development, basic events are identified in parallel. In most cases, the characteristics of the basic events allow then to be grouped. During this process, descriptions of basic events can be reviewed and kept consistent. In addition, each group of basic events may require assumptions to clarify the analysis of results. The grouping of basic events makes the quantification process of basic events easier. In more complex models, the grouping of basic events becomes more important.

2.7. Step 5. Structure Function Establishment

As shown in Table 2.2, a top event can be described using either a success tree or a failure tree. In this study, the problem is analyzed using a success tree. A structure function is the function that enables the calculation of a top event probability. Establishing a structure function according to success tree techniques is described below. This function can be described in terms of Minimal Path Sets (MPSs).

The preparatory step in establishing structure function is to identify MPSs with basic events. An MPS is a path set that leads to system success, not containing another path set as a subset. MPSs are expressed in terms of basic events. For example, if the co-occurrence of three basic events, $Y_{A,}$ Y_B, and Y_C, leads to system success, the corresponding MPS is described as MPS = $\{Y_B Y_C Y_C\}$. There are two ways of describing a structure function with MPSs: Disjunctive Normal Form (DNF) and Sum-of-Products Form (SPF). Equations 2-1 and 2-2 are DNF and SPF, respectively.

$$Y_T = \coprod_{i=1}^{n} MPS_n = 1-(1-MPS)(1-MPS)...(1-MPS_n) \quad (2.1)$$

$$Y_T = \sum_{i=1}^{N} M_i - \sum_{i=1}^{N-1}\sum_{j=i+1}^{N} M_i M_j + ... + (-1)^{N+1}\prod_{i=1}^{N} M_i \quad (2.2)$$

The next step is to substitute basic events (Y_A, Y_B) for MPSs in the structure function. Basic events can be substituted for MPSs in the DNF or SPF. For example, if there are only two MPSs in the success tree, and those are described as $MPS_1 = \{Y_A Y_C\}$, $MPS_2 = \{Y_B Y_C\}$, the structure function (Y_T) can be written as:

$$Y_T = 1-(1-MPS_1)(1-MPS_2) = 1-(1-Y_A Y_c)(1-Y_B Y_C) \quad (2.3)$$

Finally, one can further simplify this function using the fact that $Y^k = Y$ for $k>0$ because all basic events are all binary variables. The quantification of this structure function can be done by applying simple probability theory to equation (2.3) as follows:

$$P(Y_T) = P(\sum_{i=1}^{N} M_i) - P(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} M_i M_j) + ... + P((-1)^{N+1}\prod_{i=1}^{N} M_i) \quad (2.4)$$ [17]

2.8 Step 6. Basic Event Evaluation: Evaluation of Model Inputs

The main inputs to the top event probability calculation are reasonable values for basic event probabilities. There is no way to evaluate exactly the basic event probabilities. For the quantification of basic events, the following three ways can be used:

- Eliciting experts' opinions based on their experiences
- Developing metrics composed of factors that affect basic event probabilities
- Developing success trees for each basic event separately during basic event quantification process

[17] The probability of MPS can be calculated using the following rule: $P(MPS_1) = P(Y_A Y_B) = P(Y_A)P(Y_B)$

In this study, the first two approaches were developed and the quantitative analysis was done only through the elicitation of expert opinions.

2.8.1 Elicitation of Expert Opinion

The risk analysis of uncertain events inherently requires quantification of probabilities for which little or no experimental data exist. Risk assessment involves many uncertain quantities, only some fraction of which agrees with statistics and modeling. Judgment of experts is needed to supplement and interpret available information. A structured and detailed process is essential to obtaining non-skewed and informed expert knowledge[18] Experts may have well-founded opinions to justify those uncertainties. The use of judgmental probability allows for the inclusion of uncertainties in risk assessment. The quantification of expert opinion in the form of judgmental probabilities is known as ***expert-opinion elicitation***. [19] A typical procedure to obtain expert opinions is shown in Table 2.3.

Table 2.3 Procedure for Expert-Opinion Elicitation

Step	Tasks
Selection of experts	•Conduct literature survey •Utilize a professional network
Preparation of questionnaire	•Prepare questions to obtain data in a way that minimizes uncertainties and ambiguity
Collection of expert opinions	•Send the questionnaire to the experts •Receive answers from the experts
Quantification	•Aggregate multiple data obtained from experts
Interpretation of expert opinions	•Conduct a quantitative analysis •Re-contact experts as a part of fine-tuning process, if necessary

For the present study, time periods are divided based on the safeguards features of the NPT regime as shown in Table 2.4.

[18] S. V. Mladineo et al., "Guidelines for the Performance of Nonproliferation Assessments.", pp.66 -69.
[19] Bilal M. Ayyub, "Uncertainties in Expert-Opinion Elicitation for Risk Studies" (paper presented at the Proceedings of the 9th United Engineering Foundation Conference on Risk-Based Decision Making in Water Resources, Santa Barbara, CA, 2000).

Table 2.4 Classification of Time Period Concerning IAEA Safeguards Development

Time	B. Moran (2007) [20]	Carlson and Leslie (2005)[21]	Present study
1960s	Before the NPT	Level O (significant safeguards issues)	INFCIRC/66
1970s-1980s	From the NPT's entry into force in 1970 to AP in 1997	Level I (INFCIRC/153)	INFCIRC/153
1990s		Level II (INFCIRC/540 implemented satisfactorily, not yet qualified for Integrated Safeguards (IS)	INFCIRC/540
2000s	1997 to present		Matured INFCIRC/540
2010s	-	-	Integrated Safeguards System (ISS)

Multiple experts are typically chosen to increase the objectivity of quantification while decreasing biased opinions. There are several methods to handle multiple data acquired from experts and several approaches to better treat data from multiple sources. Table 2.5 lists some approaches for this treatment.

Table 2.5 Available Methods for Treating Multiple Sources

Approach	Method / Model		Reference
Mathematical aggregation approach	Simple easy-to use method	Equal-weight	Budnitz et al. (1997, SSHAC)[22]
		Quantitative weight -linear opinion pool -logarithmic opinion pool	Clemen and Winkler (1999)[23]
	Classical model		Cooke (1991)[24], Morris (1977) [25]
	Bayesian model		
Behavioral approach	Delphi method		Clemen and Winkler (1999)
	Nominal group technique		

[20] B. Moran, "An Evaluation of Safeguards Approach Options for Large Gas Centrifuge Uranium Enrichment" (paper presented at the INMM 48th Annual Meeting Tucson, AZ, July 2007).

[21] They defined five levels from Level 0 to Level IV. Level III is "Integrated safeguards satisfactorily," and Level IV is "Integrated Safeguards implemented satisfactorily for extended period." John Carlson and Russell Leslie, "Safeguards Intensity as a Function of Safeguards Status" (paper presented at the INMM 2005 Symposium, Phoenix, AZ, July 2005).

[22] R.J. Budnitz et al., "Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts, NUREG/CR-6372 " (Senior Seismic Hazard Analysis Committee (SSHAC), NUREG, 1997).

[23] R.T. Clemen and R.L. Winker, "Combining Probability Distributions from Experts in Risk Analysis," *Risk Analysis* 19, no. 2 (1999).

[24] R.M. Cooke, *Experts in Uncertainty: Opinion and Subjective Probability in Science* (Oxford, U.K.: Oxford University Press, 1991).

[25] P.A. Morris, "Combining Expert Judgements: A Bayesian Approach," *Management Science* 23, no. 7 (Mar. 1977).

In this study, the equal-weight approach is used for congregation of expert opinions. The equal-weight approach is simple and has advantages over other methodologies. In the use of this approach, two factors should be considered. First, all experts should be assumed to be equally credible. Second, extreme expert opinions should be truncated.[26]

2.8.2 Hierarchic Metrics-Index Method

The metrics should be able to relate to the characteristics of the system that needs to be analyzed. Difficulties with developing metrics include a lack of independence of the metrics, the need to facilitate the understanding and use of the results of an assessment, diverse employment of metrics.[27]

A. Hierarchic Metrics Formulation

A metric for each basic event was developed to provide a way to evaluate basic events. This method can be alternately used in the absence of experts' opinions. However, these metrics can help shape what factors experts have in mind in order to provide their evaluation. The methodology is performed in five steps as shown in Table 2.6.

Table 2.6 Procedure for Quantification of Basic Events by Index Values

Step	Process		Remarks
1	**Establishment of hierarchic metrics** -Top, intermediate, and basic metrics		All affecting factors to basic events
2	**System function establishment**	Quantitative relationship between intermediate metrics and basic metrics	Similar to the aggregation of multiple data
		Quantitative relationship between top metrics and intermediate metrics	
		Quantitative relationship between a basic event and top metrics	
3	**Basic metrics evaluation** -scores can be assigned through literature survey or available data		High (3), medium (2), low (1), None (0)
4	**Top metric value calculation** -current values with assigned values at step 3 -perfect values with high values for all basic metrics		
5	**Transformation of top metric-index numbers into probability values**		Data analysis

[26] Ham, "An Integrated Methodology for Quantitative Assessment of Proliferation Resistance of Advanced Nuclear Systems Using Probabilistic Methods".p.165.
[27] S. V. Mladineo et al., "Guidelines for the Performance of Nonproliferation Assessments." pp.32 -41.

The first step in establishing hierarchic metrics is to identify all factors affecting a top measure. A hierarchic metric is composed of several layers of metrics: top metrics, intermediate metrics, and basic metrics[28] each layer of metrics are represented as X, Y and Z, respectively as shown in Figure 2.3. In this study, basic metrics are identified in terms of individual measures or programs available in the NPT regime. In this study, top metrics include the detectability by systems (legal capabilities), the detectability by technology (technological capabilities), and a specific factor needs consideration.

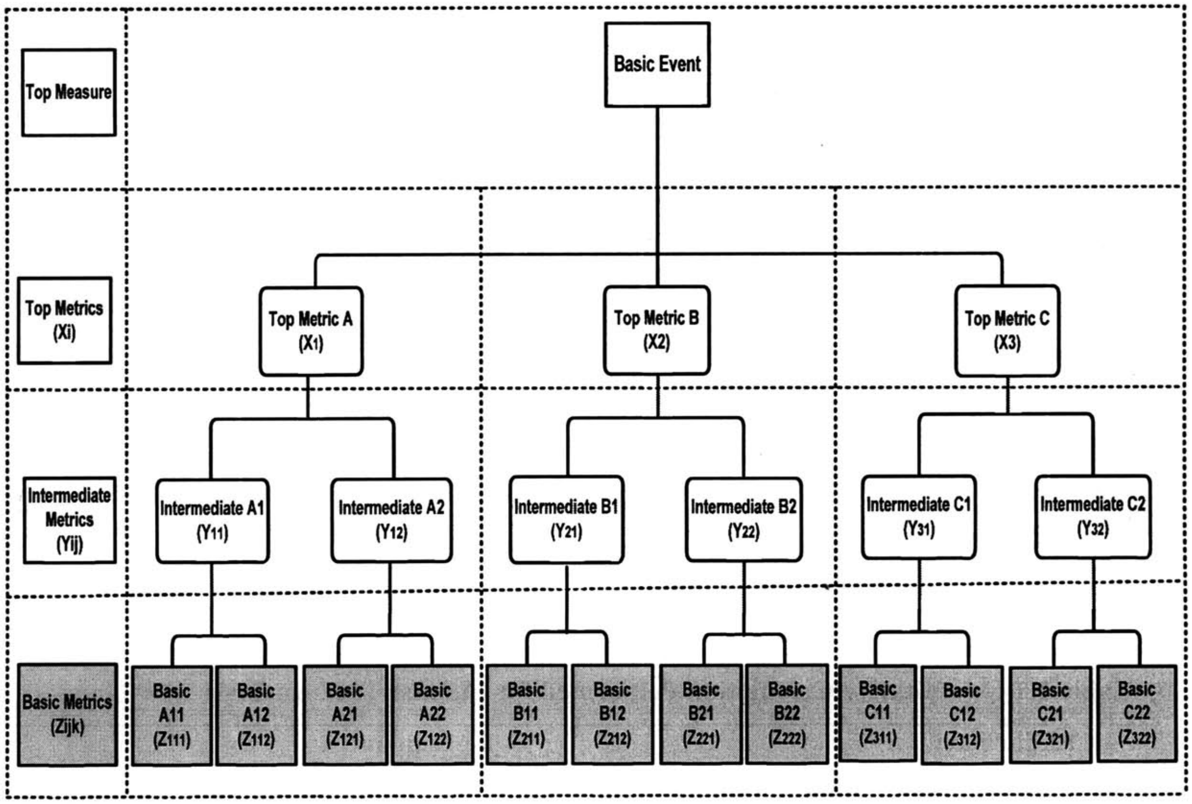

Figure 2.3 Structure of Hierarchic Metrics

B. Index Numbers for Top Measures

Index numbers are used in quantifying top measure values using a hierarchic metrics. An index number method provides a means to compare values in different settings.[29] An index number can be obtained using simple values for the current time and a predetermined base time. The base time is some arbitrary time chosen by the analyst and values for other periods determine a series of index numbers. In this study, a base period is set some time when safeguards system reaches its maximum capacity. Namely, they are obtained when all basic metric values are assigned their maximum values.

[28] For some basic metrics, affecting elements may be added to detail the basic metrics for better description.

[29] In Economics, an index number method is used as a way to standardize the measurement of numbers so that they are directly comparable.

A structure function for a hierarchic metrics can be generally represented as:

$$P(Top\,Measure) = f(\underline{X}),\ \underline{X} = \{X_1, X_2, X_3, ...X_i\} \qquad (2.5)$$

where, $X_i = f_i(\underline{Y}_i)$, $\underline{Y}_i = \{Y_{i1}, Y_{i2}, Y_{i3}, ...Y_{ij}\}$; $Y_{ij} = f_j(\underline{Z}_j)$, $\underline{Z} = \{Z_{ij1}, Z_{ij2}, Z_{ij3}, ...Z_{ijk}\}$; and i, j, and k are numbers of top, intermediate, and basic metrics, respectively.

Input values for basic metrics (Z_{111}, Z_{112}, ..., and Z_{ijk}) are obtained based on the evaluation using multiple references from 0 to 3. An index number for a top measure in hierarchic metrics is calculated through proper structure functions. These index numbers can be transformed into probability values with data analysis.[30]

2.9 Step 7. Quantification-Calculation using Saphire®

Top event probabilities in a success tree were calculated using Saphire (Include manufacturing company name and location). Two types of quantitative calculation were performed using success tree models as shown in Table 2.7. First, quantitative calculation #1 yielded top event probabilities for different types of countries under different scenarios. Second, quantitative calculation #2 provided the impact of changes in each basic event probability (i.e., available policy options) on the top event probability. Comparing the results of studies #1 and #2 may determine how the IAEA's limited resources should be prioritized when dealing with nuclear nonproliferation.

Table 2.7 Quantitative Calculation Performed for Success Tree Analysis

Classification	Description
Calculation #1: Impact of safeguards system	• At Type A countries -High level of safeguards type (Additional Protocol) -High level of domestic safeguards system -High level of cooperation with the IAEA
	• At Type B countries -Medium or Low level of safeguards (INFCIRC/153) -Medium or Low level of domestic safeguards system -Medium or Low level of cooperation with the IAEA
Calculation #2: Impact of enhanced safeguards system	• Advancement and introduction of detection technologies • Enhancement of safeguards system

[30] For instance, in the area of financial study, index values could correspond to credit ratings for each firm. Through quantitative data analysis, each range of index values is assigned a range of probability values.

Table 2.8 summarizes how these quantitative analyses can be done and what outcomes are obtained.

Table 2.8 Ways to Conduct Quantitative Analyses and Outcomes

<table>
<tr><th>Type of analysis</th><th>How to conduct?</th><th>What are obtained?</th></tr>
<tr><td>Uncertainty analysis</td><td>Insert different distribution of basic event probabilities (i.e., standard deviations)</td><td>Different distribution of the top event</td></tr>
<tr><td rowspan="2">Sensitivity analysis</td><td>Replace original basic event probabilities with multiplied values</td><td>Changes in top event probability</td></tr>
<tr><td>Obtain different top event distributions according to different expert opinions</td><td>Sensitivity to different experts</td></tr>
<tr><td rowspan="2">Importance analysis</td><td>Rank MPSs in terms of probability values in a decreasing order.</td><td>Probability for each minimal cutsets
Importance ranking for minimal cutsets</td></tr>
<tr><td>Obtain Fussell-Vesely Importance measure [a]</td><td>Risk significance evaluation of basic events</td></tr>
</table>

Note: [a] Importance measures in Probability Risk Assessment (PRA) also include the Birnbaum importance measure, Risk Reduction Worth (RRW) and Risk Achievement Worth (RAW).[31]

In the present study, Fussell-Vesely importance measure was chosen among several importance measures in order to rank the importance of individual basic events. The Fussell-Vesely (F-V) of basic event *i* (BE_i) is the fraction of the normal (baseline) Cumulative Distribution Function (CDF) would be reduced if the probability of BE_i was always zero. This can be represented as:

$$FV_i = 1 - \frac{R^{-i}}{R^0} \qquad (2.6)$$

where R^0 is the base-case risk metric, and R^{-i} is the risk metric with the probability of basic event *i* is always zero.[32]

2.10 Step 8. Quantitative Analysis: Assessment

Three types of quantitative analysis were performed with the integrated methodology: uncertainty analysis; sensitivity analysis; and importance analysis. The purpose of each analysis is as follows: First, uncertainty analysis is done to measure the 'goodness' of a result. There are two types of uncertainties: aleatory and epistemic. Aleatory uncertainty results from the inherent variability in a phenomenon that is modeled. On the contrary, epistemic uncertainty is caused by the limited knowledge about the

[31] Mohammad Modarres, *Risk Analysis in Engineering: Techniques, Tools, and Trends* (Boca Raton, FL: CRC Press, 2006).
[32] George Apostolakis, "Lecture 10 Probabilistic Calculations for 22.39 Elements of Reactor Design, Operations, and Safety " (MIT, Fall 2007)

phenomenon. Sources of uncertainties are described in Table 2.9. Second, sensitivity analysis is done to determine how sensitive a model is to changes in the value of the basic events and to changes in the structure of the success tree model. Third, importance analysis is done to depict the MPSs and basic events that most likely contribute to successful production of HEU.

Table 2.9 Sources of Uncertainties[33]

Classification		**Sources of uncertainties**
Aleatory	**Phenomenon uncertainty**	• Inherent variability in the phenomenon under consideration
	Mathematical model uncertainty	• Use of different mathematical models for describing the phenomenon in the model of the world. (i.e., success tree method)
Epistemic	**Modeling process uncertainty**	• Assumptions and approximations used in modeling process
	Parameter uncertainty	• Numerical evaluation process for basic events (expert-judged values from different experts) • Method used for the aggregation of the evaluation obtained from different experts

2.11 Summary

This study will provide insight into (a) how the NPT regime and IAEA safeguards evolved over time and (b) whether there is a close correlation between the NPT regime's effectiveness and the success of nuclear weapons proliferation. An integrated methodology was used for this study, comprised of eight separate procedures. The methodology starts with problem identification which helps to construct scenarios associated with each problem. These scenarios are subsequently translated into success trees. However, in most cases, obtaining objective input values of basic events for the quantitative evaluation of success trees can be challenging. Thus, expert opinion must be elicited in the instance where either the occurrence of basic events in the success trees is very rare or those events cannot be modeled quantitatively. It should be noted that expert judgment is subject to a high level of uncertainty due to the subjectivity of expert evaluation of basic events. In this regard, quantitative analyses are necessary to explore the reliability of models.

[33] In fact, it is precisely for problems where data are limited and where simplifying assumptions have been used that a quantitative uncertainty analysis can provide an illuminating role, to help identify how robust the conclusions about model results are, and to help target data gathering efforts. H.C. Frey, *Quantitative Analysis of Uncertainty and Variability in Environmental Policy Making* (Washington DC: AAAS/US EPA Environmental Science and Engineering Fellows Program, American Association for the Advancement of Science, 1992).

PART I IDENTIFICATION OF ROLES IN THE NPT REGIME

Part I is dedicated to identifying characteristics and capabilities of two roles at work in the Nuclear Nonproliferation Treaty (NPT) regime. Two roles are safeguarders and proliferators. Safeguarders prevent proliferators from developing nuclear weapons. Part I is essential to understanding the complex problems of nuclear proliferation that the international community is facing.

In Chapter 3, drawing upon a wide variety of empirical studies in nuclear proliferation, variables that affect the decision to initiate nuclear proliferation were identified. Those variables were then used to analyze the dynamics of nuclear proliferation using causal-loop diagrams. Chapter 4 described the overall schematic of a typical nuclear weapons program. Through this chapter, one can understand how a nuclear weapons program proceeds once the decision is made to develop nuclear weapons and what resources are required.

In Chapter 5, the NPT regime was reviewed through a literature review in political science and legal studies. The chapter starts by reviewing a general regime theory in political science and then, a regime theory was applied to the NPT regime. Through this chapter, conceptual criteria for analyzing the effectiveness and power of the NPT regime were proposed. Two criteria, resources and capabilities, were used for evaluating the power of the NPT regime and making recommendations in Chapter 15.

Chapter 6 introduces the IAEA's safeguards systems, which can be interpreted as legal capabilities of the IAEA. Through chapter 6, one can understand how the IAEA performs its verification activities and in what capacity. Chapter 7 analyzes technological capabilities of the IAEA, focused on technologies used for verification activities at declared facilities or for declared materials.

CHAPTER 3 INTERNATIONAL RELATIONS THEORY AND NUCLEAR PROLIFERATION

3.1 Introduction

Nuclear proliferation has been a critical issue since the first use of nuclear weapons in 1945. The world witnessed the annihilating power of nuclear weapons, and soon enough, major powers such as the Soviet Union, the United Kingdom, France, and China engaged in a nuclear arms race to obtain this deadly, yet attractive, power. In this chapter, I will examine the theory of nuclear proliferation from the standpoint of international politics, focusing on why some states seek nuclear weapons and under what conditions other states forbear nuclear weapons. In other words, I will review the incentives and disincentives that affect whether a state initiates a nuclear weapons program from the viewpoint of realism and liberalism, which are the two main schools of thought that explain security matters in international relations study.

This review will provide an understanding of the basic nature of nuclear proliferation, which will also be useful in developing strategies for improving nuclear nonproliferation regime. However, there is no single factor in predicting the behavior of potential proliferators because the nuclear proliferation propensity of states varies over time as the international security environment changes. As a basic approach to model the complexity of nuclear propensity, a simple causal-loop model that describes the relationship between incentives and disincentives, and nuclear propensity is proposed.

3.2 International Security Environment in the Post-Cold War Era

During the Cold War, a discernible pattern of world order existed. The international system of the Cold-War era was defined as the bipolar system by two superpowers. This period was dominated by military competition between the two superpowers and their respective allies. Countries with an alliance relationship with the superpowers could rest assured that they would be protected by their partner superpower if they faced security threats.[34] In contrast, non-nuclear weapon states that were not under the protective umbrella of a superpower perceived serious threats.[35] Structural constraints resulting from the bipolar system prevented states from acquiring nuclear weapons.

The concepts of Mutual Assured Destruction (MAD) and second-strike capability were developed in the 1960s and, then, Nuclear Détente, including the Strategic Arms Limitation Treaty (SALT) between the US and the Soviet Union were followed from the late 1960s until the early 1980s.

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[34] Peter Van Ham, *Managing Non-Proliferation Regimes in the 1990s: Power, Politics, and Policies*, (New York, NY: The Royal Institute of International Affairs, 1993). p.51.
[35] William Epstein, "Why States Go – And Don't Go – Nuclear," *Annals of the American Academy of Political and Social Science*, Vol. 430, Nuclear Proliferation: Prospects, Problems, and Proposals, (Mar.,1977), pp.16-28

After the demise of the Soviet Union and end of the Cold War, the bipolar system collapsed, but the strong and secure world order that some predicted would replace the bipolar system has not materialized. The collapse of the bipolar system unsealed the Pandora's box of long-suppressed ethnic conflicts and nationalist sentiments which had been locked during the Cold War. Nationalism, religion and transnational ethnicity have recently supplanted ideologies of the Cold War era. [36] Some call contemporary international order the unipolar system, with the only superpower being the United States, whereas others believe the world is now a multilateral system. Since the Cold War ended, the strategic importance of some regions of the world has declined, resulting in a limited engagement of two former superpowers. Some states lost their protection by one of these superpowers, and they started to prepare for the new international security system of self-help. This situation has caused instability in some regions and resulted in regional arms races in the Middle East, Southeast Asia, and Northeast Asia.[37] As a result, the possibility of nuclear proliferation has increased, and the dynamics of international relations have become more complex. It is evident that this kind of insecurity and uncertainty has inflamed the aspirations of some states to achieve nuclear status, especially when they are located in a high-conflict region. [38]

3.3 International Relations Theory for Nuclear Proliferation

Two main schools of thought in international relations theory are realism and liberalism. These two theoretical paradigms help provide theoretical explanations of state behaviors in relation to nuclear weapons proliferation. Incentives and disincentives of nuclear weapons acquisition, nuclear deterrence, the nuclear nonproliferation regime, and the roles of nuclear weapons in the future are some of the topics that fall into this realm of international politics. Furthermore, consequences of nuclear industry's growth and problems of whether the spread of nuclear weapons will contribute the stability of the world are other important issues under debate.[39]

3.3.1 Realism and Nuclear Proliferation

Realism in international relations holds that nation-states are unitary in the sense that states act as rational autonomous actors regardless of their internal nature. Based on this assumption, realism further argues the following: sovereign states are primary actors in international affairs; the main goal of states

[36] See Kjell Goldmann, Ulf Hannerz, and Charles Westin, *Nationalism and Internationalism in the Post-Cold War Era*, (London/New York: Routledge, 2000).

[37] For more discussion on regional arms race after the end of the Cold War, see Peter Van Ham (1993), pp.58-69.

[38] See more detailed discussion in T.V. Paul, *Power VS Prudence: Why Nations Forgo Nuclear Weapons?,* (Ithaca, NY: McGill-Queen's University Press, 2000), pp.18-27. Paul classified regions into high-conflict, moderate-conflict, and low-conflict regions in terms of conflict level and security dilemma, coupled with the presence of militarized inter-state disputes and crises, and the economic interdependence level. For example, a high-conflict region is characterized by protracted conflicts and enduring rivalries. States are extremely sensitive to relative gains. Interstate economic relations are minimal.

[39] Sagan and Waltz, *The Spread of Nuclear Weapons: A Debate*, (New York, NY: W.W. Norton & Company, Inc.,1995). 1st edition.

is to maintain and ensure their own security; relations between states are determined by their relative levels of power. The level of a state's power is primarily determined by the state's military and economic capabilities.[40]

Realist theory dominated the early stage of nuclear proliferation studies primarily because of the lack of information about other motivators during the Cold War.[41] Realism provides good explanations for why some states choose to acquire nuclear weapons. Rational deterrence theory[42] and hegemonic theory[43] are good examples that are based on realism. Realists see nuclear choices as the decision of the states in consideration of relative military capabilities, their participation in alliances, and their roles within the international system.

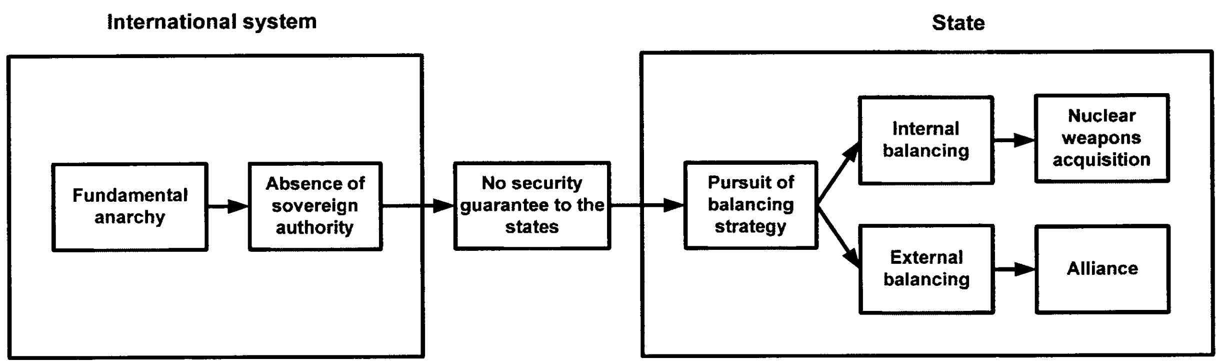

Figure 3.1 Realism and Nuclear Proliferation

Figure 3.1 shows why states seek nuclear weapons in an anarchic international system where no authority exists.[44] Realists believe the following with regard to arms acquisition: First, states acquire arms in order to protect their vital interests, especially within a self-help system.[45] Second, states need to be prepared to deter any possible attacks by acquiring arms. They believe that their neighbors may engage in military actions against them if they do not have the means to protect themselves from attacks. Third, states want to achieve superior weapons capabilities so as to increase their power and prestige

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[40] Kenneth Waltz, *Theory of International Politics*, (New York, NY: McGraw-Hill, 1979).
[41] Tanya Ogilvie-White, "Is there a Theory of Nuclear Proliferation? An Analysis of the Contemporary Debate," *The Nonproliferation Review*, (Fall, 1996), pp.43-60.
[42] Once more than one country has acquired a second-strike nuclear capability, war between then is highly unlikely to occur like in the Cold War era: mutually assured destruction (MAD). Kenneth N. Waltz, "Nuclear Myths and Political Realities," *American Political Science Review*, Vol.84, no.3 (Sep., 1990), pp.731-745.
[43] Hegemonic stability theory realists argue that the presence of a strong hegemony is what makes for a successful regime. They believe that regimes simply reflect the distribution of power in the international system.
[44] Glenn Chafetz, Hillel Abramson, and Suzette Grillot, "Role Theory and Foreign Policy: Belarussian and Ukranian Compliance with the Nuclear Nonproliferation Regime," *Political Psychology*, Vol.17, no.4, (Dec.,1996), pp.727-757.
[45] Kenneth Waltz, *Theory of International Policies*, (Reading, MA: Addison-Wesley, 1979). A "Self-help system" means the system where the actors cannot call on a higher authority to resolve difficulties or provide protection.

and preserve their autonomy. In this context, states should keep their rights to manufacture nuclear weapons.

There are limitations in the realist's explanation for nuclear proliferation. First, the concept of states' relative power is only a sufficient condition to decide nuclear proliferation. Second, the evidence of states' preference for internal balancing over external balancing has not been supported empirically. Third, realism does not explain states' voluntary forbearance of nuclear proliferation.[46] In sum, the realists do not necessarily predict that a state will proliferate, just that the state will be motivated to respond to a threat of power differential with its neighbors or competitors for restoring the balance of power in an anarchic world.[47]

3.3.2 Liberalism and Nuclear Proliferation

Liberalism in international relations holds that the configuration of interdependent state preferences determines states' behavior, unlike realism, where state capabilities are seen as critical. Institutionalism, functionalism, and constructivism fall into the category of liberalism. Liberalists, often under criticism for their naiveté about state power, hold that interdependence among state actors, democratic peace, and the effects of international institutions change states' behavior.[48] However, liberalists can also provide an explanation for nuclear choices in regions where low levels of interdependency among states exists.[49]

As far as international politics are concerned, liberalists believe the following: First, the use of force in international politics can be minimized by appealing to human nature and promoting cooperation. Second, liberalists focus on ways to avoid conflict among states by regulating state behavior through international institutions or international regimes because they believe actors' interests and capabilities can be altered by those international systems.[50] Third, interaction between states is not limited to the political and security relations but also economic and cultural activities. Therefore, economic interdependence will not only serve economic objectives but decrease the need to resolve differences between states using armed conflicts.

Liberal institutionalists provide the key explanations for norms and rules contained in regimes. As for nuclear nonproliferation, liberalism explains nuclear forbearance, interstate dependence, and the effect of regimes and norms on states' behavior very well. Liberalists believe that regimes or international cooperation come about through a convergence of state interests, and that international institutions help create the synthesis of interests.[51] In contrast, realists argue that regimes can be

[46] Glenn Chafetz, Hillel Abramson, and Suzette Grillot (1996).
[47] Robert Holcombe (MIT M.A. Dissertation, 2006), p.27.
[48] Taking Preferences Seriously: A Liberal Theory of International Politics, International Organization, Vol.51, no.4, (Autumn 1997), pp.513-53.
[49] T.V. Paul (2000), p.14.
[50] Andrew Moravcsik, (1997).
[51] Regimes facilitate cooperation by establishing standards of behavior which signal to all other members that individual states are in fact cooperating. When all states expect the other participants to cooperate, the probability of sustaining cooperation increases dramatically.

successful only if there is a strong hegemonic power that forces other states to cooperate. The theoretical background of ***regime theory*** will be detailed in Chapter 5.

3.4 Factors Affecting Nuclear Proliferation

A first step in the study of how a state reaches a decision to go nuclear is to find affecting factors in the decision making process. Factors affecting incentives or disincentives for nuclear proliferation can be classified in three dimensions: (i) environmental contexts (international or domestic)[52]; (ii) political, military, and economic factors; and (iii) time-frame (short-term and long-term or preemptive and/or reactive). Furthermore, some factors can affect both nuclear proliferation as well as nuclear forbearance, depending on whether they increase or decrease in relative magnitude. The international and domestic environment of states is shaped by the political or diplomatic, economic, and military status of countries. Some factors may vary over the short term, while others do not change over the long term. Table 3.1 shows a summary of research that attempts to model the dynamics of nuclear proliferation propensity.

Table 3.1 Summary of Research with regard to Modeling of Nuclear Proliferation

Authors	Factors considered	Methods
Meyer (1986)	1.Motive conditions or incentives[53] (1) international political power/prestige incentives (2) military/security incentives, (3) domestic political incentives 2.Dissuasive conditions	Nuclear Propensity model
Sagan (1997) [54]	(1) The security model: nuclear weapons and international threats (2) The domestic politics model: nuclear pork and parochial interest (3) The norms model: Nuclear symbols and state identity	Qualitative description
Singh, Way [55] **(2004)**	1.Depedent variables 2.Explanatory variables (1) Technological determinants- (2) External determinants-the presence (or absence) of a security threat and a security guarantee (3) Internal or domestic determinants-democracy, liberalizing governments, an autonomous domestic elite, and symbolic/status motivations	Survival and hazard methods & multinomial logistic regressions

[52] T.V. Paul (2000) looked at nuclear proliferation at the regional level by using variables of the level of conflict and co-operation, and the level of politico-security interdependence in a given region. T.V. Paul (2000), p.15.
[53] Stephen M. Meyer, *The Dynamics of Nuclear Proliferation*, (Chicago, IL: The University of Chicago Press, 1986). p.46.
[54] Scott D. Sagan, "Why Do States Build Nuclear Weapons?: Three Models in Search of a Bomb," *International Security*, Vol.21, no.3 (Winter, 1996-1997), pp.54-86.
[55] Sonali Singh and Christopher R. Way, "The Correlates of Nuclear Proliferation: A Quantitative Test," *The Journal of Conflict Resolution*, Vol.48, no.6 (Dec., 2004), pp.859-885.

(Continued)

Jo and Gartzke [56] **(2008)**	1. Opportunity: economic capacity and nuclear technology diffusion 2. Willingness: (1) International security: conventional threat, nuclear threat, nuclear defense pact, diplomatic isolation (2) Domestic politics: domestic unrest, democracy (3) Norms: NPT membership, NPT system effect (4) Status: major power status, regional power status	Probit regression analysis and White robust estimation[57]

As can be seen, no single factor can explain the complexity of nuclear proliferation. Most single factors do not appear to have a direct correlation to a state's decision to proliferate nuclear weapons, meaning that, normally, a state makes this decision based on its own evaluation of a larger set of factors. However, there is one exception. A state's assessment of its international security threat does seem to yield a close correlation to whether that state chooses or does not choose to go nuclear.

3.5 Incentives for Acquiring Nuclear Weapons

Form the realists' perspective that sees state power as the essence of explaining nuclear proliferation, all nations want to enhance their power and, thus, improve their position of influence in the world. It is a reasonable assumption that, in a world with few nuclear weapons, a state which breaks out of nuclear disarmament might be able to exert more leverage than in a world where nuclear weapons are abundant. The incentives for nuclear weapon acquisition embrace a broad range of political, military, and economic motivations. For example, Ham (1994) sees that three factors are important in making countries want to acquire nuclear weapons: acute threat perceptions, general national security concerns, and political prestige.[58]

All possible factors affecting nuclear incentives are further detailed in Table 3.2. Among these factors that influence a state's decision, some factors vary over the short-term, while others take a long time to change. As shown in Table 3.2, the factors that do not change over the long-term are described as "***fixed***," while situational factors that are subject to change depending on the situation are defined as "***situational***." The validation of time duration for each factor goes beyond the scope of this study; however, it would be valuable to look at variations of each factor over time. If a proliferator has an enduring capacity, such as self-reliable domestic resources like petroleum or a strategic leverage holder based on its geopolitical importance, it could willingly take a risk of going nuclear.[59]

[56] Dong-Joon Jo and Erik Gartzke, "Determinants of Nuclear Weapons Proliferation," *Journal of Conflict Resolution,* Vol.51, no.1, (Feb., 2007), pp.167-194.
[57] Jo and Gartzke used a standard cross-section time-series data structure and classified variables into dependent variables and independent variables.
[58] Peter Van Ham (1994), p.73.
[59] Iran has a large amount of petroleum, while North Korea has a strategic holder mainly due to its successful efforts in creating tensions in Far East Asia region.

Table 3.2 Incentives for the Acquisition of Nuclear Weapons

Environment	Factors	Description	Time-frame
International [60]	Political power /prestige	•Aspiration for political prestige (regional or global) [61] -Aspire to be global or regional power status/pretensions -Assert political and military independence -Deter regional intervention by superpower	F
		•Overcoming International *pariah status* [62] -Demonstrate national viability (by pariah countries) to force international community to sit up and take note. [63]	S
		•Overcoming an inferior position within an alliance structure -Enhance bargaining position within an alliance with a nuclear power -Assert politico-military independence	F
International	Military /Security	•Emergence of Nuclear Threat[64] -Response to a security threat from a nuclear-armed adversary -Response to an adversary with *a latent capacity of manufacturing nuclear weapons*[65]	S
		•Disappearance of security assurance[66] / alliance	S
		•Response to an adversary with an overwhelming conventional military threat[67]	F

(Continued)

[60] Stephen M. Meyer (1986).
[61] Williams Epstein (1977).
[62] Some states do not always acknowledge the international norm and do not show regime-guided behavior. They fear being in a situation of precarious diplomatic isolation, without credible security support or political moorings inside great power alliance structures. Peter Van Ham (1993), pp.72-73. For more information how to determine "pariah state" Robert E. Harkavy, "Pariah States and Nuclear Proliferation", *International Organization*, Vol.35, no.1 (Winter 1981), pp. 135-163. Harkavy defined Israel and South Africa, as pariah states, and Taiwan and South Korea as "quasi-pariah" states.
[63] It is true that having enrichment and reprocessing capabilities is one of important components of national security. It can demonstrate to surrounding countries that a state has achieved a high-tech level of industry.
[64] Stephen M. Meyer (1986), pp.56-60.
[65] This factor is considered contentious and varies over time in different countries. A state adjacent to an adversary with a nuclear latent capacity may consider two opposite situations: the initiation of a nuclear arms race and the creation of superiority over its adversary. The case of Brazil and Argentina shows this contradictory explanation.
[66] Generally there exist two types of nuclear security assurance. One is positive security assurance, which provides a so-called nuclear-umbrella, while the other one simply promises not to use or threaten to use nuclear weapons.
[67] Peter V. Ham, p.51. The Gulf war showed that developing countries' conventional weapons cannot hold against Western high-tech electronic, precision warfare. This has strengthened the conviction of some states that non-conventional weapons are the sole guarantee of national security.

Domestic	**Domestic politics**[68]	•Maintenance of unstable regime (use of nationalism)[69] -Overcoming domestic turmoil -Enhancing political leader's power position under domestic unrest	S
		•Public's national pride -Raising a morale or pride by defense establishments -Raising national self-image after major military defeat -Raising national leader's popularity	S
	Economic benefits[70]	•Economic/industrial spinoffs[71]	S
		•Change in defense strategy from conventional forces to nuclear forces because of intolerable economic burden[72]	S
		•Possession of uranium reserves	F

Note: F and S stand for fixed and situational, respectively.

Table 3.3 examines some states that sought to develop nuclear weapons by detailing the corresponding incentives for making that decision. It should be noted that the factors analyzed in Table 3.3 were the ones considered by states at the time of the decision because surrounding environments that states face vary over time. If there is a state with natural uranium reserves, it is always a viable option to develop nuclear weapons programs. It is a less viable alternative for states that must seek out uranium on the international black market. As can be seen, security threats and nuclear ambition are the principal factors in motivating states to launch nuclear weapons programs.

Iran and North Korea are good examples of supporting nuclear incentives. These states have either real or perceived enemies that are much stronger militarily than those states. Achieving nuclear weapons would allow them to dramatically improve their security situation. Also, once a state achieves or is close to achieving nuclear weapons, their international status increases. The leaders of those states have been successful in forcing the major international players to acknowledge them and draw them into the negotiation table. They can be viewed as players on the international scene. The leaders can show their populace that they have become major players who can negotiate from positions of power. As a result, the morale of their populace can increase, and the leaders can strengthen their political positions.

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68 Stephen M. Meyer (1986), pp.63-64.

69 A domestic turmoil can be overcome by diverting domestic attention or direct domestic energies away from domestic problems. And the power position of political leaders can be strengthened by inciting nationalism, especially in the case of military government

70 William Epstein (1977), pp. 22-24.

71 Economic benefits from nuclear proliferation are well-described in the paper written by William Epstein (1977); and George Quester "Reducing the Incentives to Proliferation," *The Annals of the American Academy of Political and Social Science*. Vol. 430, (March 1977), pp.70-81.

72 Stephen M. Meyer (1986), p.65.

Table 3.3 Cases of Motivation for Nuclear Weapons[73]

Country	Domestic context	International / Regional context
Argentina	•Economic spinoff •Morale booster after the defeat by the U.K. •Military government	•A security threat from a nuclear-armed adversary (Britain) •Ambition for regional power prestige (overcoming sense of inferiority to Brazil)
Brazil	•Domestic politics •Military government •Uranium reserves	•Global and regional power prestige •Response to an adversary with a latent capacity of manufacturing nuclear weapons
France	•Morale booster after military defeats	•Global power prestige
Iran	•Regime change •Uranium reserves •National pride	•Regional power prestige •Deterrence from a superpower •Security threat from Israel
Israel	•Uranium reserves	•Security threats from surrounding Arab countries, as well as, the Soviet Union.
North Korea	•Political tools •National pride •Uranium reserves	•Diplomatic leverage •Security threats from the US forces in South Korea
Pakistan	•Defeat by India in 1971	•Security threat from India (nuclear-armed adversary)
South Africa	•Political tools •Uranium reserves	•Security threat from the Soviet Union and surrounding countries
Switzerland	•Fear of a possible German acquisition of nuclear weapons	•Security threat from the Soviet Union
Sweden	•Uranium reserves	•Security threat from the Soviet Union

3.6 Disincentives for Acquiring Nuclear Weaponry

Disincentives are mainly explained by liberalism. Disincentives are a set of dissuasive conditions that tend to work against nuclear proliferation and work throughout the whole nuclear weapons programs. Some states do not feel that they need nuclear weapons and other states shut down their nuclear weapons programs in the middle of development or even after the successful testing of nuclear weapons. A couple of member states of the former Soviet Union forwent their nuclear weapons that they inherited and returned them to Russia.

If disincentives are put into a context of time sequence of occurrences, some factors are either the results of proliferation activities within proliferation states themselves or the responses from the international community after detection, while others are preemptive ones deterring states from making the decision to "go-nuclear." Disincentives given by international community can be divided into "sticks and carrots." Carrots are given under the condition that a proliferator forgoes a nuclear weapons

[73] The cases of Argentina, Brazil, Israel, Pakistan, Sweden, and Switzerland are excerpted from T.V. Paul (2000).

program. On the contrary, sticks are punishments that include the withdrawal of currently-existing economic and technical assistance, economic military sanctions,[74] and diplomatic isolations.[75]

Table 3.4 Disincentives of Nuclear Weapons Program[76]

Environment	Factors	Description	Features		
International	Political	•Fear of negative consequences of violating international legal commitments (NPT, NWFZ): Worries about the resultant political fallout and international punishments in case of violation	S	P	F
		•Acquisition of peaceful reputation and good international images by complying with legal commitments •Joining or re-joining the international mainstream	C	R	S
	Economic	•Economic returns : Financial and technical assistance in return for termination of nuclear weapons program[77] •Ending of economic sanctions or economic isolation[78]	C	R	S
International	Military[79]	•*Fear/punishment of causing regional proliferation*: existence of a rival with a latent capacity	S	P/ R	S
		•Fear/punishment of preemptive threats[80] -Preemptive intervention by a major power -Military sanctions by the UN Security Council	S	P/R	S
		•Security Assurance Provision from nuclear powers -Nuclear security: positive or negative security assurance -Conventional security: assurance of a supply of conventional arms to a threatened country[81]	C	P/R	S
		•Reduction or termination of security threat -Nuclear threat: *nuclear disarmament*[82], establishment of NWFZ[83] -Conventional military threat: arms reduction	C	P/R	S

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[74] See George Quester (1977) for various types of sanctions.

[75] Joseph Nye sees security guarantees, technical assistance, sanctions, multilateral persuasion, and declaratory policy as diplomatic measures. For more discussion, see Joseph S. Nye, Jr. Part II.3 Diplomatic Measures in eds. Robert D. Blackwell and Albert Carnesale, *New Nuclear Nations: Consequences for U.S. Policy*, (New York, NY: Council on Foreign Relations Book, 1993).

[76] Stephen M. Meyer (1986), pp.67-74.

[77] Ukraine chose to forgo its nuclear weapons in return for economic assistance and security assurances from both the United States and Russia. On this issue see T.V. Paul (2000), p.118.

[78] Gary C. Hufbauer, Jeffrey J. Schott, Kimberley A. Elliot and Barbara Oegg, *Economic Sanctions Reconsidered: History and Current Policy*, (Washington D.C.: Institute for International Economic, 2007), 3rd edition. They analyzed the effectiveness of economic sanctions as a tool to achieve foreign policy objectives. They used two dependent variables to measure a sanction's success: policy result and sanctions. These two variables with values from 1 to 4 are multiplied and it is counted as a sanctions success if the values are equal or greater than 9.

[79] Michèle A. Flournoy, Part III.6 Implications for U.S. Military Strategy, in eds. Robert D. Blackwell and Albert Carnesale, *New Nuclear Nations: Consequences for U.S. Policy*, (New York, NY: Council on Foreign Relations Book, 1993).

[80] Both Sweden and Switzerland initiated nuclear weapons programs but forewent them due to the fear that the Soviet Union might conduct a preemptive attack. See T.V. Paul (2000) pp.84-98.

[81] William Epstein (1977).

[82] This issue is contentious in the nuclear nonproliferation field. Epstein claims only drastic nuclear disarmament would reverse the nuclear arms race, where as George Quester claims that the halting of nuclear proliferation will require a low-key and subtle approach since excessive abstraction and clarity can lose low visibility of nuclear matters. William Epstein, (1977), pp.16-28; and George Quester (1977).

[83] Brazil and Argentina became non-nuclear through a bilateral process and established the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC).

(Continued)

Domestic Environment	**Economic**	•Defense Expenditure Burden: Intolerable economic burden caused by nuclear weapons program[84]	-	P/ R	S
	Domestic Politics	•Fear of unauthorized seizure by antigovernment groups [a]		R	S
		•Termination of need to use nuclear weapons as a political tool in order to acquire national leader's popularity -Power transition from military government to civilian government		R	S

Notes
[a] Domestic unrest that leads to instability and inability to control nuclear weapons
[b] P and R denotes preemptive and reactive, respectively.
[c] S and C stand for stick and carrot, respectively.
[d] F and S stand for fixed and situational, respectively.

Table 3.4 details a list of the disincentives that a state would have to consider in making its decision of whether or not to continue with a nuclear weapons program. In most cases, disincentives to nuclear proliferations come from the fears of proliferating states about negative consequences or responses from the international community as a consequence of the revelation of its nuclear proliferation program.

Table 3.5 shows some states that started nuclear weapons programs or acquired nuclear weapons, but ended up forbearing them. Generally it would be very difficult to clearly define when each state started; however, a reasonable assumption will be probably when they started to build nuclear facilities. As far as the end of nuclear weapons program is concerned, the announcement by national leaders or the participation in the NPT is regarded as its termination.

Table 3.5 Cases of States that Discarded Nuclear Weapons Program by Disincentives

Countries	**Domestic**	**International**	**Duration of nuclear weapons program** [a,b,d]
Argentina	•Economic burden •Fear of causing regional nuclear proliferation •Transition to Civilian government	•Economic incentives (promoting economic cooperation) •Re-join the international community	Mid 1970s to 1983
Brazil	•Transition to Civilian government	•Economic incentives (promoting economic cooperation)	1975 to 1990
Libya	Not available	•Economic incentives •Consequences of violating international commitments	Mid 1970s to 2003

(Continued)

[84] The costs of a large array of delivery vehicles and other support systems far exceed those of nuclear warheads. Erwin Häckel, Chapter 3. Towards non-nuclear security: costs, benefits, requisites, pp.56-79, Regina Cowen Karp, ed., *Security Without Nuclear Weapons?: Deterrent Perspectives on Non-Nuclear Security*, (New York, NY: Oxford University Press, 1992). P.71. For further information on specific numbers, see Stephen Schwarz, Atomic Audit: The Costs and Consequences of U.S. Nuclear Weapons Since 1940, (Washington D.C.: Brookings Institution Press, 1998)

South Africa	•Economic burden •Political instability •Domestic political change (political reform)	•Economic assistance •Diplomatic pressure •Disappearance of threats with the collapse of Communism	1970 to 1979
South Korea	•Domestic instability due to the assassination of the former leader	•Diplomatic pressures and incentives •Military incentives •Threats of economic sanctions	1972 to 1981
Switzerland	•Political leaders' benefit cost analyses •Division of political leaders on nuclear proliferation decision (domestic opposition)	•Fear of preemptive attack from potential adversaries •Fear of causing regional nuclear proliferation (West Germany)	1945 to 1969
Sweden[85]			1952 to 1968
Taiwan [d]	Not available	•Diplomatic pressure •Security assurance •Threats of economic sanctions	1974 to 1978 and 1988
Ukraine	•Economic burden for maintenance costs	•Economic assistance •Security assurance •Diplomatic incentives: Joining international community	1991 to 1994

Notes
[a] Argentina, Libya, South Korea, and Taiwan from Meyer (1986), p.8.
[b] Argentina, Brazil, Sweden, Switzerland, South Korea and Ukraine are from Paul (2000).
[c] Some data from Table 1. Leonard Spector (1994), p.36.
[d] Meyer (1986), p.133.

Figure 3.2 shows the presumed duration of nuclear weapons programs in nine states. The figure prescribes important information about when their nuclear weapons programs initiated and how long nuclear weapons programs proceeded.

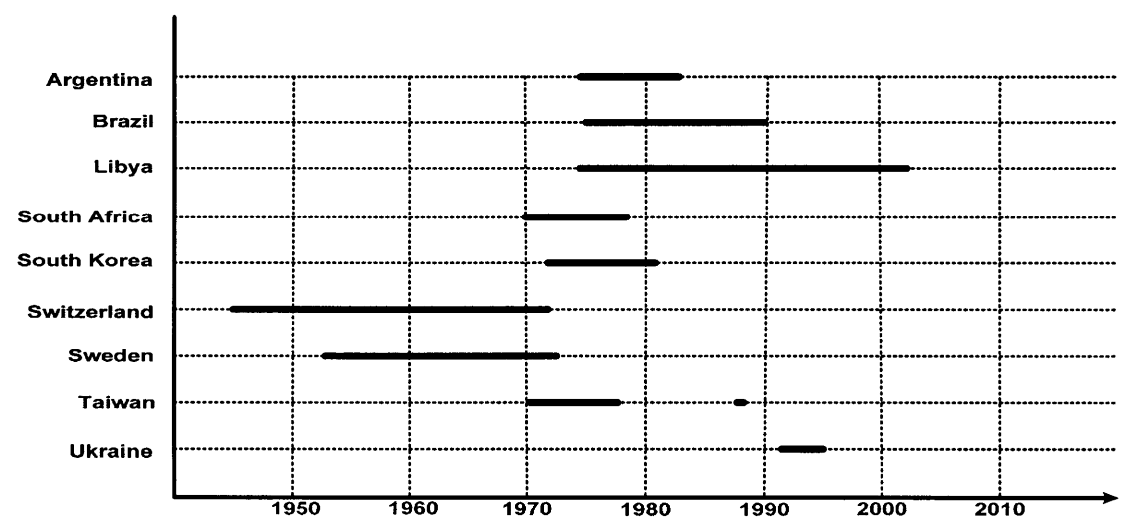


Figure 3.2 Duration of Nuclear Weapons Programs in States

85 The Swedes realized that it would be difficult to possess both strong conventional and nuclear capabilities simultaneously. T.V. Paul (2000), pp. 88-89. The Swedes feared that West Germany could acquire nuclear weapons. T.V. Paul (2000). p.90

3.7 Complexity of Nuclear Proliferation

Many factors affect the initiation and termination of nuclear weapons program. It seems that the international environment and a nation's power prestige are correlated to nuclear proliferation. However, it seems to be more challenging to prove that domestic factors affect the decisions about nuclear proliferation. Table 3.6 shows the results of an analysis of the correlation between domestic factors and the nuclear proliferation decision. Sing and Way (2004) and Jo and Gartzke (2007) claim that the technological level of states might have been related to their nuclear propensity. In contrast, Meyer (1986) claims that only domestic politics affect the decision for nuclear proliferation.

Table 3.6 Research on Relations between Factors and Go-nuclear Decision

Author	Technological level	Economic status	Domestic Politics
Sing and Way	O	X	X
Meyer	X	N/A	O
Jo and Gartzke	O	O	X

A. Complexity of Domestic Political Stability

Argentina and Brazil halted their nuclear weapons programs after the advent of democratic government in 1983 and 1990, respectively.[86] However, Singh and Way (2004) concluded that neither democratization nor democracy has any discernible effects on nuclear proliferation decision. Jo and Gartzke (2007) supported their claim that the levels of democracy and domestic unrest do not affect to the initiation of nuclear weapons programs. Meyer (1986) suggests two disincentive factors could be considered with regard to the domestic political stability of each state such as domestic unrest and risk of unauthorized seizure.[87] He concludes that domestic unrest is a factor proven sufficiently though historical references were relatively few.

B. Complexity of Economy

It seems that a minimum level of economic size in terms of GDP is required to initiate nuclear weapons programs. Häckel claims that an economic analysis with regard to nuclear proliferation policy can provide objective criteria to understand nuclear proliferation policy of states. He suggests that a broad range of national resources is required for a nuclear weapons program such that most developing countries cannot reach a nuclear weapons program unless they have the sheer size of their human resources such as China and India.[88]

[86] Leonard S. Spector, Strategic Warning and New Nuclear States, Defense Intelligence Journal, Vol.3, (1994), pp.33-52.
[87] Stephen M. Meyer (1986), pp.64-71.
[88] Erwin Häckel (1992), pp.56-79.

Singh and Way (2004) also conclude that nuclear proliferation is reasonably well accounted for by the level of economic development. They used GDP per capita, GDP squared and industrial capacity index to measure the effects of technological determinants. Singh and Way found very interesting results with their model. The model revealed that at low levels of GDP, further economic growth is proportional to the exploration of the nuclear option, but at high levels of GDP, the effect levels off and reverses, probably because of the fear of economic sanctions. As the economy of a state grows, involvement in the world economy (i.e., economic interdependence) will increase though it remains somewhat unclear to conclude that a causal linkage exists.[89] This is a very meaningful result because this implies that economic sanctions might work more efficiently in a state a high level of economic interdependence, as Paul (2000) described.[90]

C. Complexity of Technology Level

Meyer (1986) claims that there is no common description of the trend or the relation between the technological level of states and nuclear proliferation. He set up three models to identify the relationship between the technological level and the nuclear proliferation process as follows: [91]

- Model I: latent capacity longevity and the number of proliferation decisions
- Model II: the ratio of proliferation decisions to latent capacity opportunity
- Model III: the rate of proliferation decisions to levels of nuclear development (nuclear infrastructure level)

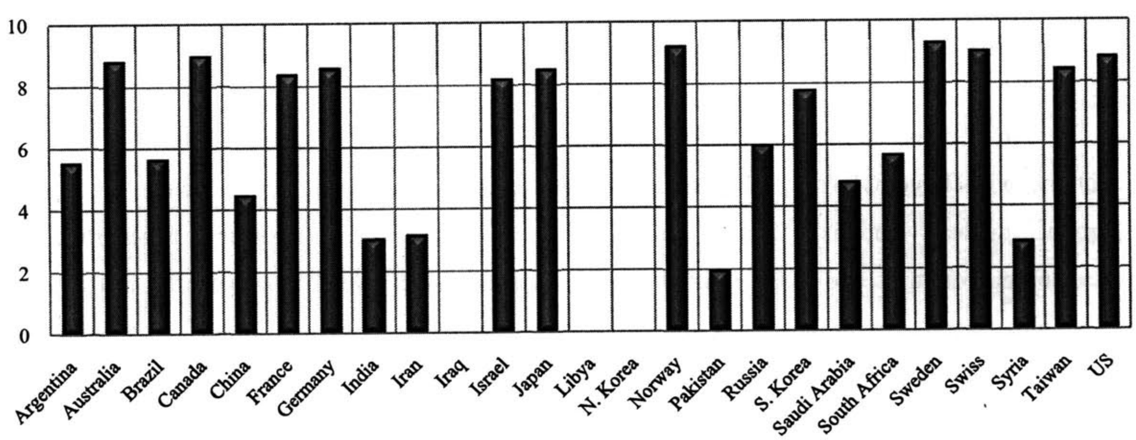
In contrast to Meyer's study (1986), it was believed that only technologically sophisticated nations with large GDPs, well-educated human resources and indigenous nuclear facilities could produce nuclear weapons. Häckel claims that the lack of qualified manpower is a generic feature of developing countries and is the most difficult challenge to get over.[92] However, the fast diffusion of technology enables more countries to have sophisticated engineering and industrial capacity. Nuclear technology has diversified, which makes it harder to track illegal or clandestine acquisition of nuclear technology. The development of the internet and dual-use items contributes to the ease of nuclear technology acquisition. We can carefully conclude that possessing the technological capability is not a necessary condition to initiate nuclear weapons programs mainly due to the global spread of nuclear technology, which lowered the latent capacity threshold requirement. However, the technological level of a state can be a sufficient condition because a minimum level of technology seems to be required.

[89] For more information, see Singh and Way, p.882
[90] T.V. Paul (2000), pp.18-27.
[91] Stephen Meyer (1986), pp.75-91
[92] Erwin Häckel (1992), p.71.

3.8 Analysis with Published Index Values

Twenty five states that were or are conceived as having nuclear weapons programs were selected for a simple analysis to review the relationship between nuclear proliferation propensity, and economic and technological capabilities, and domestic politics. For an analysis, indices published by international institutions were used, including Science and Technology Capacity Index (STCI), Knowledge Economy Index (KEI), Human Development Index (HDI), Gross Domestic Product (GDP), and World Governance Indicators (WGI) [See Appendix A].

Iran, North Korea and Pakistan have low values of economy- and technology-related index values as shown in Figure 3.3 (a), (b), and (c) they overcame those difficulties in developing their nuclear weapons programs. North Korea spends approximately one third of their GDP on their military,[93] which seems to allow them to overcome this factor. Furthermore, this might be attributed to a lowered technology threshold resulting from the spread of nuclear technology. As can be seen from Figure 3.3, only (f), Political Stability and Absence of Violence Indicator (one of six types of governance indicators), seems to be related to the propensity of nuclear proliferation of states. Most of states with negative values used to have sought nuclear weapons and are seeking nuclear weapons. However, it seems that this indicator does not seem to apply in the case of North Korea because of North Korean regime's tight control over its populace and intolerance for dissent.

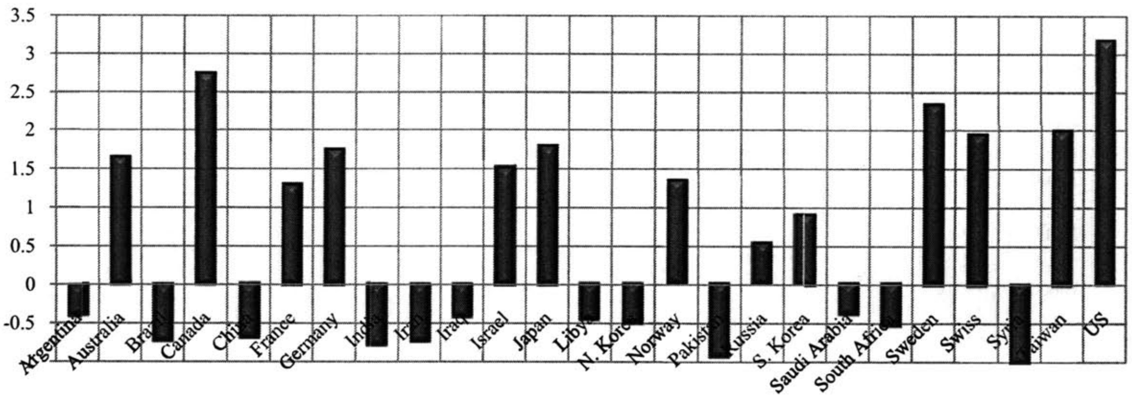


(a) Knowledge Economy Index (KEI)

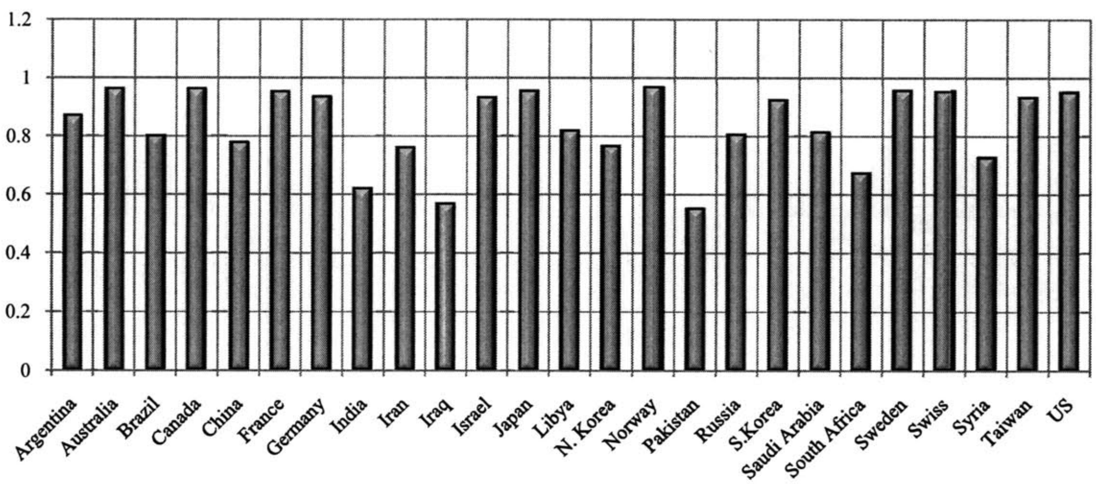
Note: Index values are not available for Iraq, Libya, and North Korea.

(Continued)

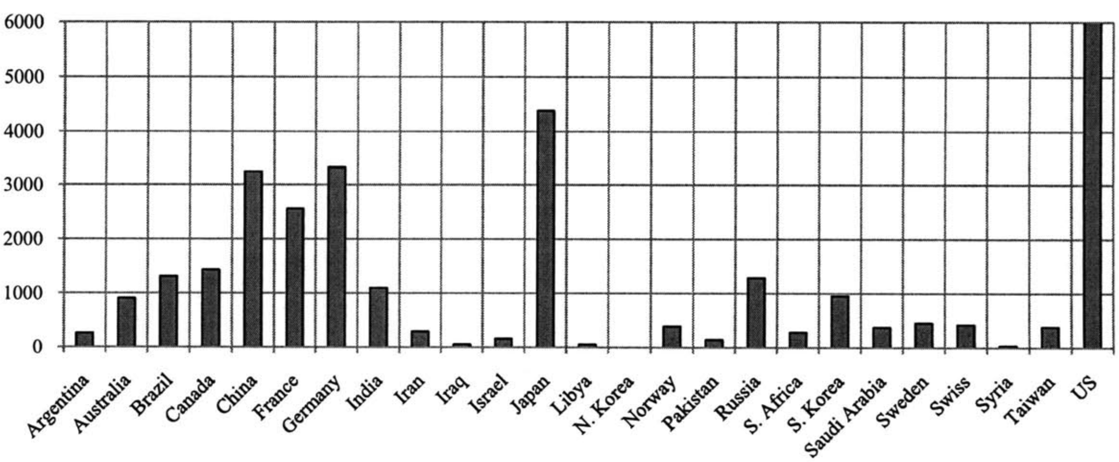
[93] CNN, "Facts on North Korea: One of the world's most secretive nations," CNN, February 10, 2005. May 4, 2009, <http://edition.cnn.com/2004/WORLD/asiapcf/04/22/nkorea.facts/index.html> Military expenditures account for 31.3 percent of GDP expenditures.



(b) Science and Technology Capacity Index (STCI)



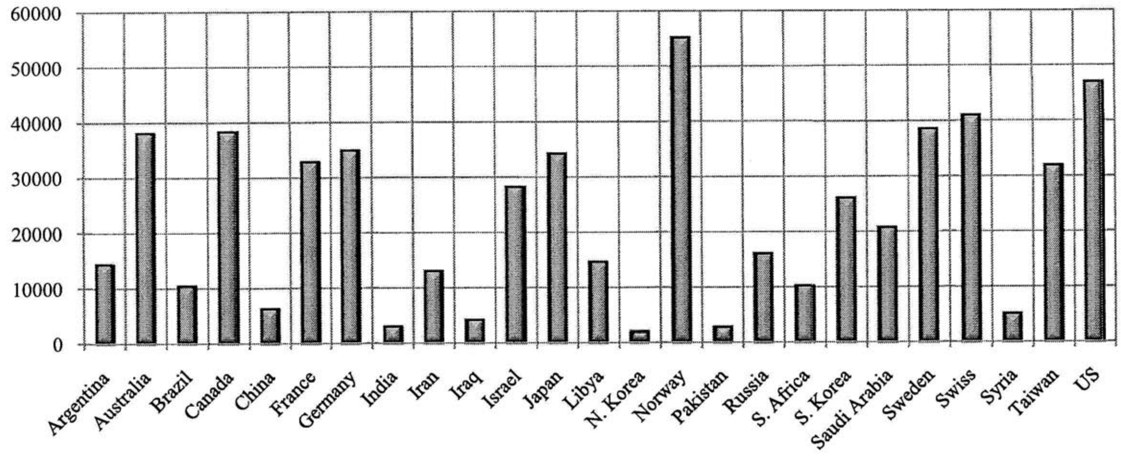
(c) Human Development Index (HDI)



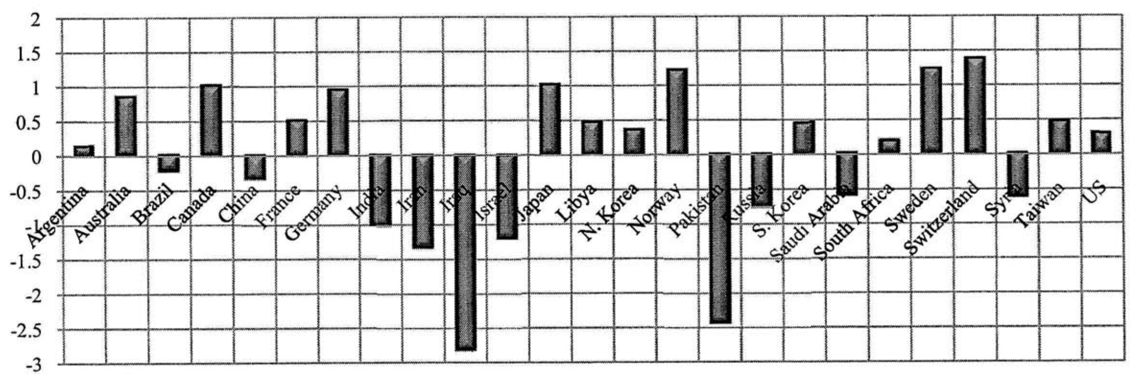
(d) Gross Domestic Product (GDP) in U.S. trillion dollars

Note: The U.S. GDP is 13,843 trillions of dollars and truncated for better description.

(Continued)



(e) GDP per Capita in U.S. dollars

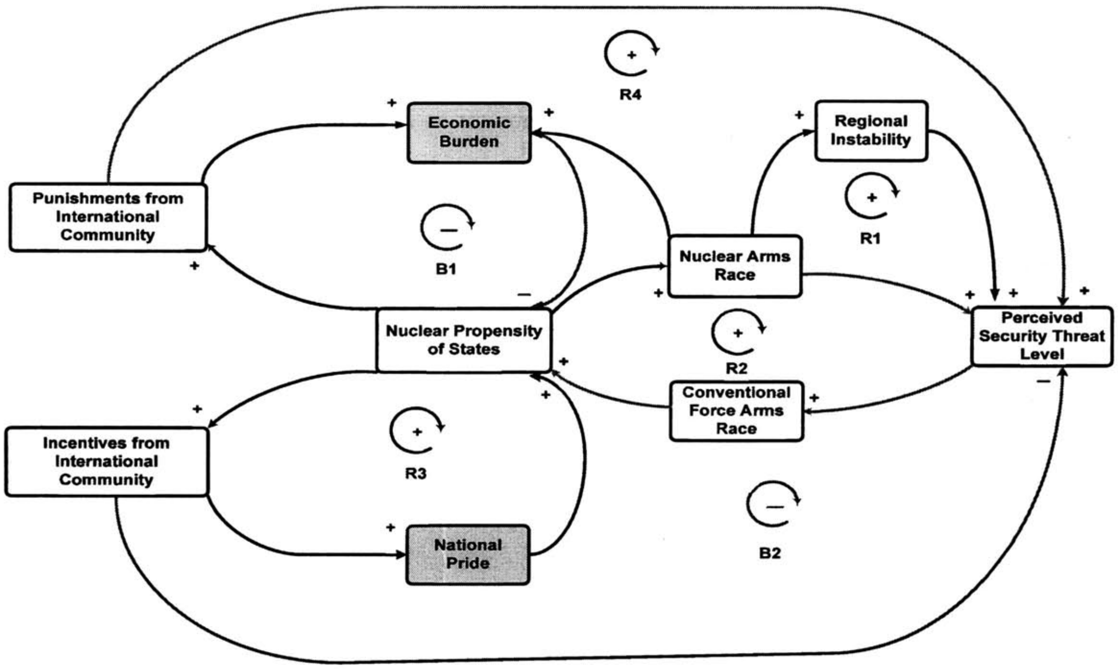


(f) Political Stability and Absence of Violence Indicator

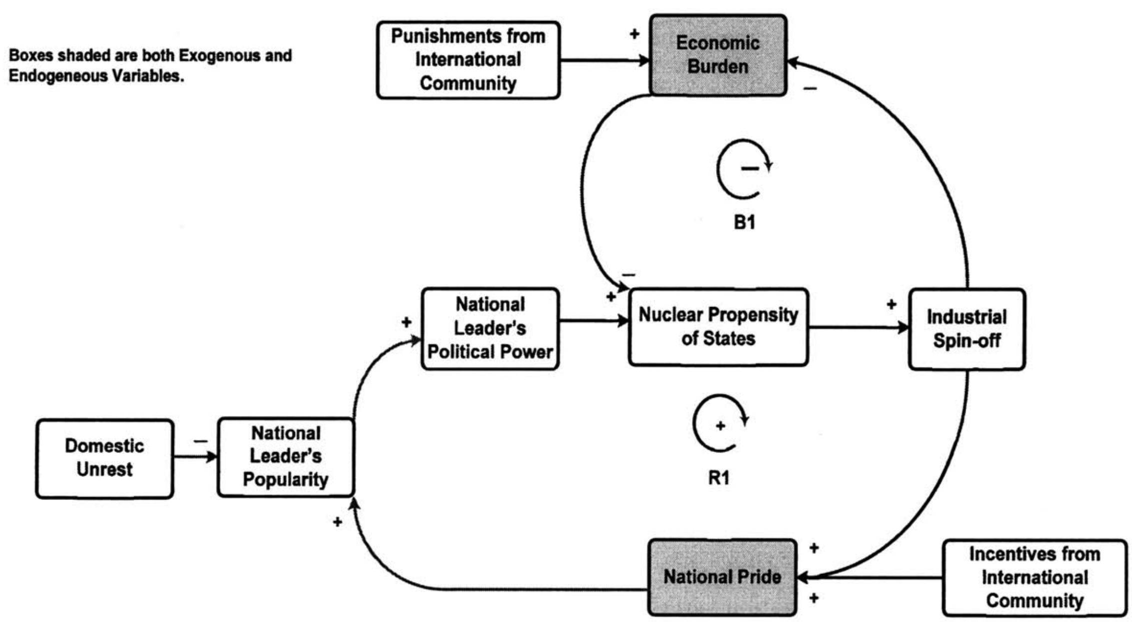
Figure 3.3 Index Values of Countries

3.9 Causal-loop Diagrams for the Dynamics of Nuclear Proliferation

Meyer (1986) exhibited the time trend of nuclear proliferation in terms of nuclear propensity based on specific motivational variables he defined. A causal-loop diagram can be drawn to describe these dynamics of nuclear proliferation over time as shown in Figure 3.4. In the causal loop diagram, only situational factors were considered among various nuclear proliferation determinants for the description of dynamics.



(a) Nuclear Propensity Affected by International Environment



(b) Nuclear Propensity Affected by Domestic Environment

Figure 3.4 Nuclear Propensity and Affecting Situational Factors[94]

[94] B, D denotes a balancing loop and a reinforcing loop respectively.

Through the causal-loop diagram in Figure 3.4, we can see how the NPT regime or the international community can work for the nonproliferation of nuclear weapons. For example, the international community can develop ways to enhance balancing loops and to disconnect reinforcing loops. The role of the NPT regime can be very important as an external force to break causal loops within the system through various means.

3.10 National Leader's Decision

A process that leads to a decision on whether a country will "go-nuclear or not" is very complex as described above. All of these factors should be applied on a case-by-case approach. [95] The decision on the initiation of nuclear weapons programs is likely to be dependent on a benefit and cost analysis (BCA), in other words, how a decision maker weighs each component of benefits and costs. National leaders make the decision to "go-nuclear or not" in consideration of both domestic and international environments surrounding the state. Basically, a decision to initiate a nuclear weapons program is made through the complex analysis of perceived benefits and costs in a reasonable and careful way. The benefits can be advantages of being nuclear powers and rewards from the international community when states terminate their nuclear proliferation processes. The costs of seeking a program are the risk of an unfavorable attitude on the world stage and penalties from the international community in the form of sanctions, in various ranges and varying degrees. Iran, North Korea, and Pakistan stay the course with their nuclear weapons program despite the disincentives offered by the international community. It is clear that the leaders of these states estimate that the benefit from nuclear weapons outweighs the punishment.

To explain the complex mechanism of nuclear proliferation, ***role theory*** was suggested as a comprehensive and promising theory. Glenn Chafetz et al. (1996) suggest that roles of states can be created by the combination of an actor's subjective understandings of role conceptions, role expectations, and the particular context where the role is being acted out. These roles are not deterministic, so they change over time at different states.[96] Moreover, the dispositions of national leaders can be important factors in states' decision. Hymans (2006) introduced the concept of National Identity Conceptions (NICs) of a state's identity in terms of status dimension and solidarity dimension. Hymans measured two dimensions and used the data in analyzing a state's nuclear decision.[97] A propensity for nuclear proliferation varies when national leaders change at each state. Iran's case clearly shows how the leader of a state plays a pivotal role in "going nuclear."

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[95] George Quester (1977).
[96] Glenn Chafetz, Hillel Abramson, and Suzette Grillot (1996).
[97] Jacques E.C. Hymans, *The Psychology of Nuclear Proliferation: Identity, Emotions, and Foreign Policy*, (Cambridge, MA: Cambridge University Press, 2006).

3.11 Conclusion

A variety of factors that can affect a state's decision to pursue nuclear proliferation was reviewed based on the theories of realism and liberalism. The two theories have their own pros and cons in explaining the nuclear proliferation of states and international politics; however, realism has a tendency to over-predict arms acquisition, whereas liberalism underestimates it. Among various factors that affect the "go-nuclear or don't go-nuclear decision," security threats are considered to be the most important one to international relations theorists. In this regard, Iran, Pakistan, and North Korea all have either real or perceived enemies that are much stronger militarily than those states. Achieving nuclear weapons would allow those states to dramatically improve their security situation and they can be viewed as players who can negotiate from positions of power on the international scene.

In reality, nuclear proliferation is far more complex than security concerns alone because other factors such as economic, political and domestic factors should be taken into consideration. Moreover, international and domestic environments change over time. A national leader's technical and political confidence and perception of his nation's role seem to also be critical in making a decision to go nuclear. A national leader should be confident that his country has a reasonable amount of economic resources and technological resources for going nuclear in the anticipation of negative consequences. If a national leader has a strong NIC as a nuclear power, it would further increase the nuclear propensity of his state. In this regard, the dispositions of leaders should be considered as important factors for the description of nuclear proliferation.

CHAPTER 4 NUCLEAR WEAPONS PROGRAM

4.1 Introduction

This chapter reviews a nuclear weapons program from a technical point of view. An extensive range of technological capabilities are required for a nuclear weapons program. Once the "go –nuclear" decision is made, a nuclear weapons program will start with the building of human resources and end with the testing of developed nuclear weapons. A very important factor is the type of fissile material, plutonium or uranium, used for the nuclear weapons because different designs and nuclear facilities are required to produce each material, owing to different properties and production paths. Different nuclear weapon designs, each of which evolved over time, require different materials for detonation. Those designs include pure fission weapons, fusion-boosted fission weapons, and two-stage thermonuclear weapons.

Available resources and nuclear latent capacity of a proliferation state, including a technology level, the available budget, and the availability of nuclear materials will decide the context of a nuclear weapons program. These factors will determine the time required to complete the nuclear weapons program. In this regard, it is important to understand what components are required and what procedures should be taken to make a nuclear weapons program successful. This chapter provides an understanding of a nuclear weapons program to help elucidate the generic procedure of a nuclear weapons program in terms of resources and capabilities.

4.2 Steps of Nuclear Weapons Program

A nuclear weapons program can be broadly defined as a program that includes nuclear warheads, advanced delivery systems, secure command and control facilities, and an operative strategic doctrine. Alternatively, a nuclear weapons program can be narrowly defined as simply a program manufacturing a nuclear explosive device. For the purposes of this study, the latter definition will be used. A nuclear weapons program is often divided into two categories, ***weaponization activities*** and ***fissile material acquisition activities***. This is not only to stress the importance of acquiring fissile material but also to highlight weaknesses of IAEA safeguards in the detection of weaponization activities because the role of current IAEA safeguards is focused on nuclear material. [98]

[98] Carlson and Leslie, "Safeguards Intensity as a Function of Safeguards Status".

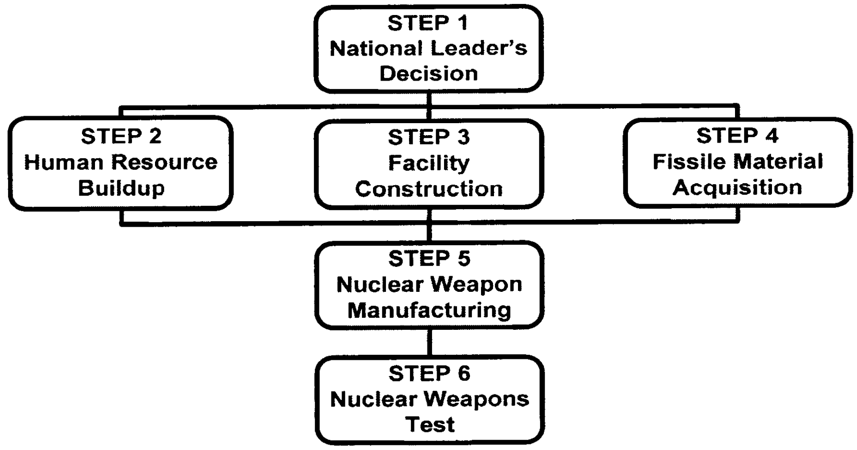

Figure 4.1 Nuclear Weapons Development Program of Potential Proliferators

Figure 4.1 shows the general steps to acquire nuclear capabilities within proliferation states. As can be seen from the figure, the first step is the decision to "go-nuclear" by the leaders of proliferation states. Then, a proliferator initiates a nuclear weapons program by building human resources and constructing nuclear facilities. For step 2 through step 6, one or more steps can be skipped, depending on the level of latent capacity or on whether external supports are available. The U.S. Department of Defense (DOD)'s Militarily Critical Technologies List (MCTL) provides a good overview of what technologies are required for a nuclear weapons program. The list explains nuclear weapons technology in great detail, coupled with tables that contain technology parameters and reference data for each technology. [99]

4.3 Fissile Materials for Nuclear Warhead

Uranium 235 (U-235) and plutonium 239 (Pu-239) are the most common, verified fissile materials for making nuclear warheads. In addition to these materials, U-233, Neptunium 237 (Np-237), and Americium 241 (Am-241) are also fissile materials from which nuclear warheads could be made.[100] However, they are not preferred over HEU and separated plutonium. For example, a Neptunium bomb

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[99] U.S. Department of Defense, "Militarily Critical Technologies List (MCTL), Part II: Weapons of Mass Destruction Technologies, Section 5-Nuclear Weapons Technology." <http://www.fas.org/irp/threat/mctl98-2/p2sec05.pdf>, The Militarily Critical Technologies List (MCTL), is a detailed and structured compendium of the technologies the Department of Defense (DoD) assesses as critical to maintaining superior United States military capabilities. The MCTL is used as a technical foundation for U.S. proposals for export control in the New Forum, Missile Technology Control Regime, Nuclear Suppliers Groups, Australia Group, and other nonproliferation regimes. The MCTL is used as a reference for evaluating potential technology transfers and technical reports and scientific papers for public release. The information is used to determine if the proposed transaction would result in transfer that would permit potential adversaries access to technologies, not whether a transfer should or should not be approved.

[100] The United States, at least, has tested designs containing U-233. France, and perhaps other nuclear weapon states, may have experimented with neptunium-237 in nuclear tests. International Panel on Fissile Materials (IPFM), "Global Fissile Material Report 2008: Scope and Verification of a Fissile Material (Cutoff) Treaty," (2008).

requires high-energy neutrons to initiate nuclear fission and Am-241 emits highly penetrating gamma rays that increase the radioactive exposure of any personnel handling the material. In addition, bare critical masses of Neptunium and Americium are rather large: 73 kilograms and 60 kilograms, respectively.[101] Each fissile material has its own unique features with regard to the nuclear fission reaction. More importantly for this study, each fissile material requires a different pathway for acquisition. Tables 4.1 and 4.2 show the different features of Pu-239 and U-235 as weapons-usable fissile material. The critical mass for each differs over each design because each design has a different mechanism of neutron generation and nuclear fission chain reaction.

Table 4.1 Comparison between Uranium and Plutonium for Nuclear Weapons

Criteria	U-235	Evaluation	Pu-239
Critical mass	20-25 kg	<	8 kg
ν (thermal) [a]	2.418	<	2.871
η (thermal) [a]	2.068	<	2.145
α (thermal) [a]	0.169	>	0.362
Effective Energy Released [b]	192.9±0.5 MeV	<	198.5±0.8

Notes
[a] Lamarsh and Baratta (2001)[102]
[b] James Duderstadt (1976)[103]

Table 4.2 Critical Masses of Fissile Materials[104]

Material		Bare sphere (kg)	Fully reflected sphere (kg)
Highly Enriched Uranium		52	17
WGPu	**(α phase of Pu-239)**	10	4
	(δ phase of Pu-239)[105]	16	6
U-233		15	6

[101] Kenton J. Moody, Ian D. Hutcheon, and Patrick M. Grant, *Nuclear Forensics Analysis* (Boca Raton, FL: CRC Press Inc., 2005).
[102] John R. Larmarsh and Anthony J. Baratta, *Introduction to Nuclear Engineering*, 3rd ed. (Upper Saddle River, NJ: Prentice Hall, Inc., 2001).,p.82. α is the capture-to-fission ratio, η is the average number of neutrons emitted per neutron absorbed in the mixture, and ν is the average number of neutrons released per fission.
[103] James J. Duderstadt and Louis J. Hamilton, *Nuclear Reactor Analysis* (Ann Arbor, MI: John Wiley & Sons Inc., 1976).,p.67. The value of the effective energy released in and following fission of the principal isotopes by thermal neutron.
[104] Moody, Hutcheon, and Grant, *Nuclear Forensics Analysis.*
[105] J. Carson Mark, "Explosive Properties of Reactor-Grade Plutonium," *Science & Global Security* 4 (1993).. Plutonium metal can exist in six allotropic forms corresponding to six different crystalline configurations. The two forms most often mentioned with respect to weapons are these two phases. (α phase density = 19.6, and δ phase density =15.7 [gram/cm^3]

4.3.1. Uranium

The fundamental question is to determine how much uranium and in what form/enrichment is required to make a nuclear bomb. Below 10 per cent, enriched metallic uranium cannot be made to explode because the critical mass, the minimum quantity of fissionable material necessary for a nuclear explosion, is essentially infinite. The IAEA uses "a Significant Quantity (SQ)"[106], which is based on an estimate of minimum critical mass of uranium required to make a nuclear weapon. The value of critical mass depends on the specific isotope, material properties, and the type of nuclear weapon design. It is generally regarded that 25 kilograms of uranium enriched to about 80 percent U-235 would be necessary for an implosion bomb. Table 4.3 shows definitions of uranium according to U-235 enrichment ratio.

Table 4.3 Definition of Uranium With Respect To U-235 Enrichment Ratio

Class	Definition	U-235
Depleted Uranium (DU)	Uranium in which the abundance of the isotope U-235 is less than that occurring in natural uranium, e.g., uranium in spent fuel from natural uranium fuelled reactors and tails from uranium enrichment processes.	Less than 0.71%
Natural Uranium (NU)	Uranium as it occurs in nature, having an atomic weight of approximately 238 and containing minute quantities of U-234, about 0.7% of U-235 and 99.3% of U-238.	0.71%
Low Enriched Uranium (LEU)	Enriched uranium containing less than 20% of the isotope U-235. LEU is considered a special fissionable material and an indirect use material.	More than 0.71% and less than 20%
Highly Enriched Uranium (HEU)	Any mixture of U-235 with the more abundant, non-nuclear-explosive isotope U-238 in which the U-235 concentration is 20 % or more Any mixture of U-233 when the U-233 concentration is 12 % or more HEU is considered a special fissionable material and a direct use material.	More than 20%
Weapons-Grade Uranium (WGU)	Weapons-grade uranium, generally higher than 93 percent enriched uranium.	More than 93 %

106 As for uranium, 75 kg of U-235 in HEU and 25 kg of U-235 in LEU.

As the uranium enrichment ratio increases, the critical mass decreases significantly as shown in Figure 4.2. The use a good neutron reflector and a sophisticated implosion system would further decreases the required critical mass. As uranium enrichment reaches 20 percent (HEU), uranium then can be considered a highly sensitive material. Assuming that a uranium enrichment facility operates with a tail's assay of 0.25 percent U-235, 197.34 kilogram of natural uranium feed is required to produce 1 kilogram of WGU, which means a total of 4.93 metric tons of natural uranium feed for manufacturing one nuclear bomb.

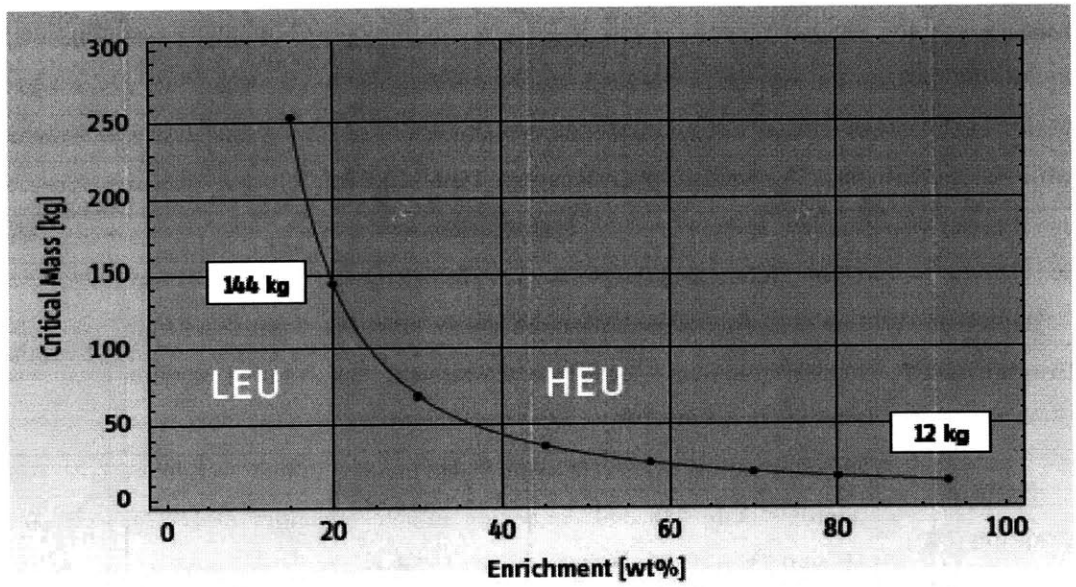

Figure 4.2 Relationship between Critical Mass and Uranium Enrichment Ratio[107]

4.3.2 Plutonium

Pu-239, which is the only fissile material that can be used for nuclear bombs among the plutonium isotopes, is produced when the most common isotope of uranium, U-238, absorbs a neutron and then decays to plutonium. It is produced in varying quantities in virtually all operating nuclear reactors. As fuel in a reactor is exposed to longer and longer periods of neutron irradiation, higher isotopes of plutonium build up as some of the plutonium absorbs additional neutrons, thereby creating Pu-240, Pu-241, and so on. Pu-238 also builds up from a chain of neutron absorptions and radioactive decays starting from U-235. However, except for Pu-239, other plutonium isotopes create some difficulties for the design and fabrication of nuclear weapons as follows:

- Pu-238 decays relatively rapidly, thereby significantly increasing the rate of heat generation in the material.

[107] A. Glaser, *Making Highly Enriched Uranium* (Princeton University, 2007 [cited Mar. 3 2009]); available from http://www.princeton.edu/~aglaser/lecture2007_makingheu.pdf.

• Pu-240 has a high rate of spontaneous fission (more than Pu-239), meaning that the plutonium in the device will continually produce many background neutrons, which have the potential to reduce weapon yield by starting the chain reaction prematurely

• Pu-241 has a half-life of 14-year and results in Am-241

Table 4.4 shows the classification of plutonium grades according to different plutonium isotope concentration ratios.

Table 4.4 Classification of Plutonium

Isotopic grade	Isotopic composition [a]					Pu-240 [108]	Pu-239 [109]
	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242		
Super-grade	-	98.0%	2.0%	-	-	no more than 3%	N/A
Weapons-grade	0.012%	93.8%	5.8%	0.35%	0.022%	less than 7%	typically about 93 %
Fuel grade	N/A					from 7 to 19 %	between 80 and 93 %
Reactor grade	1.3%	60.3%	24.3%	9.1%	5.0%	over 19%	less than 80 percent
Mixed Oxide (MOX) grade	N/A					30 % or more	N/A

Note: [a] Carson Mark (1993), pp. 111-128.

Materials that contain plutonium can be classified into five grades in terms of the ratio of Pu240 to all isotopes of plutonium or Pu-239 to all isotopes of plutonium. Weapons-grade and super-grade plutonium are well-suited for nuclear weapons. However, there is some debate as to whether nuclear weapons can be made with reactor-grade plutonium. It is generally felt that it should be possible to make low-yield weapons (up to a few kilotons) from reactor grade plutonium.[110] Some weapons experts are of the opinion that, with a sophisticated design, a reactor grade plutonium fission weapon can have as much of a yield as one made with weapons grade plutonium (up to about 20 kilotons). However, a reactor grade weapon would use more plutonium for the same yield. Reactor grade plutonium is also more difficult to handle and engineer.

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[108] U.S. Department of Energy, "Plutonium: The First 50 Years. United States Plutonium Production, Acquisition, and Utilization from 1944 to 1994," (1996).

[109] U.S. Department of Energy, "Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives," (January 1997).

[110] R. W. Selden, *Reactor Plutonium and Nuclear Explosives* (Center for Science, Technology and Security Policy, [cited May 23 2008]); available from http://cstsp.aaas.org/files/selden.pdf.

4.4 Design of Nuclear Weapons

4.4.1 Pure Fission Weapons

Pure fission weapons are the first generation design and are often called *one-stage fission* or *atomic bombs*. These weapons were the ones built first and used in real warfare. Two types of pure fission weapons are available according to the design of the detonation mechanism as shown Figure 4.3.

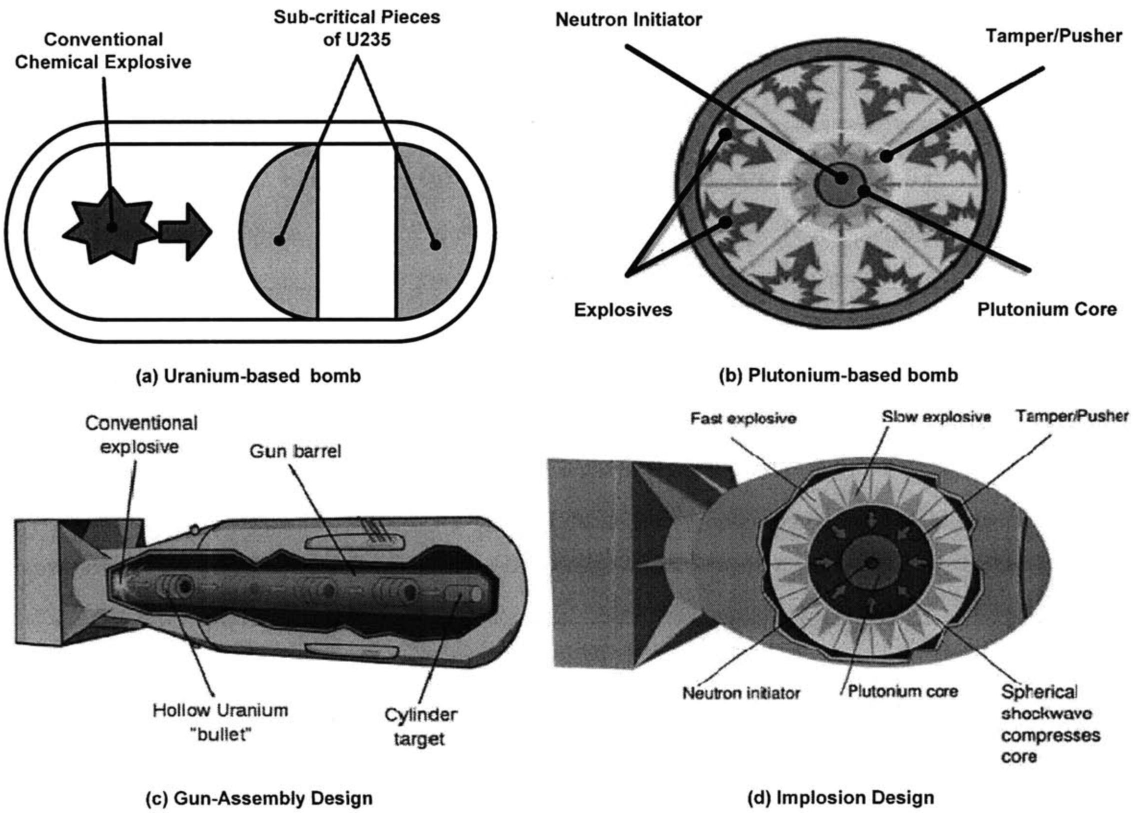

Figure 4.3 Designs of Pure Fission Bombs[111]

For pure fission bombs, the differences in detonation mechanisms are mainly due to the different properties of Pu-239 and U-235. Table 4.5 details important differences between a gun-assembly design and an implosion design. A gun assembly design typically uses uranium, whereas an implosion design uses plutonium. It should be noted that a gun assembly design is less complicated than an implosion design in terms of manufacturability and it is therefore more reliable.

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[111] Wikipedia, *Nuclear Weapon Design.*

Table 4.5 Comparison of Two Designs of Pure Nuclear Weapons

	Gun assembly design	**Implosion design**
Detonator[112]	Gun-type detonator	Implosion-type detonator
Fissile material	Uranium	Pu-239, (Possibly U-235)
Examples	• South Africa[113] • U.S. *Little Boy*[114] • Pakistan[115]	• U.S. *Trinity* and *Fatman* bombs dropped on Nagasaki • North Korea
Neutron initiator	A strong source of alpha particles[116]	A source of neutrons
Compression time of material	Milliseconds	Microseconds
Weight	Heavy	Light (less material is required)
Reliability	Certain (test is not required)	Uncertain (test is required)
Technology threshold	Low	High
Usability for missiles	• Not adequate for a compact design	• Compact design for loading ballistic missiles or strategic bombers

4.4.2. Fusion-boosted Fission Weapons

Fusion-boosted fission weapons or boosted fission weapons are the second generation design and this design can greatly reduce the amount of fissile material required in the nuclear warhead. It is known that fusion boosting by tritium and deuterium (T/D) gas can contribute to the increase in weapon's fission energy release. As shown in Figure 4.4, the primary part of a fusion-boosted weapon consists of three components: the central spherical plutonium 'pit', the beryllium 'pit liner', and surrounding high-explosives. Beryllium is used as the reflector material. [117]

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112 J.D. Dyson, *Documentation and Diagrams of the Atomic Bomb: File Courtesy of Outlaw Labs* ([cited May 1 2008]); available from http://www.nuc.berkeley.edu/neutronics/todd/nuc.bomb.html.

113 South Africa manufactured five nuclear weapons with gun-assembly design but had conducted no nuclear tests of their gun-assembled devices.

114 The design of Little Boy, 80% of U-235 60 kg, 48 kg of U-235, the bomb dropped on Hiroshima, had not been proof tested before the war shot.

115 Marko Beljac, *Pakistan and the Prospects for Nuclear Terrorism* (Australian Policy Online, 2008 [cited May 8 2008]); available from http://apo.org.au/commentary/pakistan-and-prospects-nuclear-terrorism.

116 U.S. Department of Defense, "Militarily Critical Technologies List (MCTL), Part II: Weapons of Mass Destruction Technologies, Section 5-Nuclear Weapons Technology." Po-210 or some similarly active alpha emitter. The South African devices did not use any neutron source other than background radiation.

117 GlobalSecurity.org, *Weapons of Mass Destruction (WMD), Beryllium* ([cited May 24 2008]); available from www.globalsecurity/org/wmd/intro/beryllium/htm.

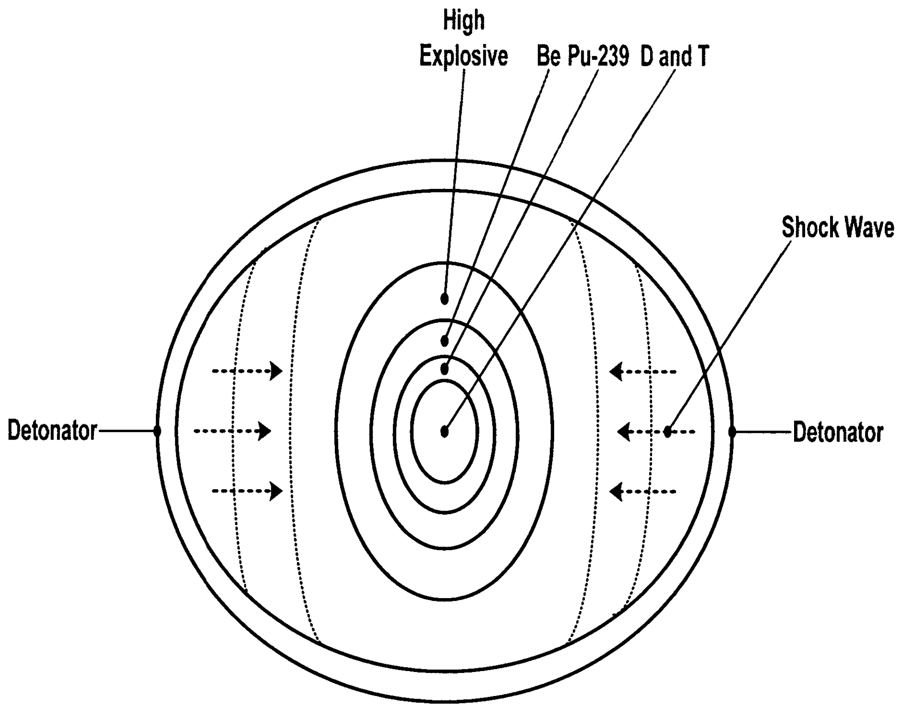


Figure 4.4 Design of Fusion-boosted Fission Weapons [U.S. Swan Device][118]

In this design, once the detonators create a chemical explosion, the fission reaction is initiated. The high temperature and pressure from fission reactions will make a mixture of tritium and deuterium gas fuse into helium and release neutrons. The neutrons generated from the fusion reaction will start a large number of new chain reactions as long as the pit remains critical. The fusion reaction of tritium and deuterium can be described as follows:

$$^{2}_{1}D + ^{3}_{1}T \rightarrow ^{4}_{2}He + ^{1}_{0}n + 17.6\,(MeV) \qquad (4.1)$$

4.4.3 Two-stage Thermonuclear Weapons – 3rd Generation Design

Thermonuclear weapons are the third generation design. They constitute an advanced design of fusion-boosted fission weapons and are often called ***hyrdogen bomb***. Figure 4.5 shows the ***Teller-Ulam*** design, which is the most well-known design of a multi-stage thermonuclear weapons.

[118] Wikipedia, *Nuclear Weapon Design* ([cited Mar. 3 2008]); available from http://en.wikipedia.org/wiki/Thermonuclear_weapon.

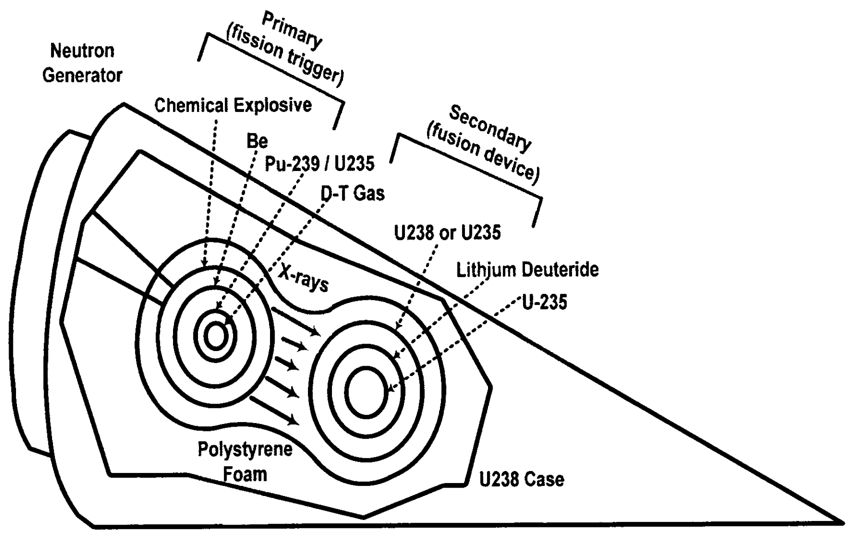


Figure 4.5 Drawing of Two-Stage Thermonuclear Weapon[119]

In this design, the reaction first starts with the detonation of chemical explosives that surround a plutonium pit. The explosive force compresses the pit and neutrons are introduced into the pit by a neutron generator. Through these two processes, a fission reaction occurs in the primary section. The fission reaction mechanism in this bomb design, up to this stage, is the same as that in a fusion-boosted fission bomb. As a result of the fission reaction, x-rays are emitted and absorbed in the casing of U-238, thereby heating a very thin layer that lines the casing to high temperature and turning polystyrene foam to plasma. The plasma re-radiates thermal energy, thereby compressing the secondary and causing fissile material in the secondary to initiate fission. Simultaneously, lithium-6 deuteride (fusion fuel) begins a fusion reaction and emits neutrons which cause the tamper to undergo fission. This is the second fission reaction in a bomb.[120]

4.5 Human Resource Capacity Build-Up

A nuclear weapons program starts with the assembly of human resources. The build-up of qualified manpower including scientists, engineers, technicians, skilled workers, planners and administrators is critical throughout the process of a nuclear weapons program. [121]They must be able to conduct a wide range of theoretical and practical tasks related to the design, development, testing, and manufacture of a

[119] Ibid. The W87 Warhead Design
[120]The Nuclear Weapon Archive, *Section 4.0 Engineering and Design of Nuclear Weapons* ([cited April 4 2008]); available from http://nuclearweaponarchive.org/Nwfaq/Nfaq4.html.
[121] It is estimated that the thousands of manpower generally is required. More than ten thousand personnel were involved in Iraqi nuclear weapons program.Jeffery Richelson, "Can the Intelligence Community Keep Pace with the Threat?," in *Nuclear Proliferation after the Cold War*, ed. Mitchell Reiss and Robert Litwak (Washington. D.C.: The Woodrow Wilson Center Press, 1994).

nuclear weapon. Even though nuclear technologies can be imported, proliferators must have a foundation of internal capability. The rationale for the need for internal capability is obvious. The more effective the internal capability, the higher the domestic learning efforts during technology transfer; and the more successful efforts will be at acquiring further technology. [122]

In order to educate nuclear physicists and nuclear engineers, many states have sent students and professionals abroad for education to acquire the basic expertise that can be easily diverted for a nuclear program. Most nuclear weapon experts in proliferation states received their initial education in the United States, Britain, or Germany. After the completion of academic study, they have obtained additional expertise through specialized training sessions at companies or institutes, the demonstration of equipment or technology, practical training on the use of purchased equipment, or discussions with foreign experts.[123]They can use their knowledge in establishing nuclear programs at the college level and building nuclear research facilities with the help of foreign experts, i.e., nuclear cooperation.

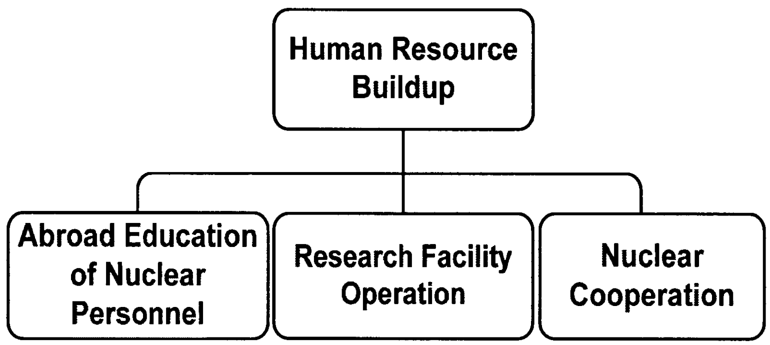


Figure 4.6 Components for Human Resources Establishment

4.6 Nuclear Facility Construction

Under the NPT regime, there is nothing illegal about any state having enrichment or reprocessing technology. Typically, the initial step to construct a nuclear facility is through a contract with states that have advanced nuclear technologies. A national decision will be made whether to build a declared or a clandestine facility for nuclear weapon development. Once the technology for both construction and operation have been accumulated, potential proliferators may try to build a clandestine, dedicated facility for nuclear weapon development program. In that case, potential proliferators must obtain dual-use items via various routes including the nuclear black market.

[122] Gillian Marcelle, *Policy Briefs, Technology Acquisition and Domestic Learning* (Jan. 1 2007 [cited Feb. 5 2009]); available from http://www.scidev.net/en/policy-briefs/technology-acquisition-and-domestic-learning.html.. However, the case of Libya was an exception, it just tried to import Turn-Key gas centrifuge to save time and overcome technical threshold.

[123] Institute for Science and International Security (ISIS), *Iraq's Acquisition of Gas Centrifuge Technology Part II: Recruitment of Karl Heinz Schaab* ([cited Mar. 3 2008]); available from http://www.exportcontrols.org/centpart2.html.

Figure 4.7 shows the kinds of nuclear facilities that are required for the acquisition of highly enriched uranium (HEU) and plutonium. As earlier mentioned, some states have sought two paths simultaneously, whereas others have chosen a single dedicated path.

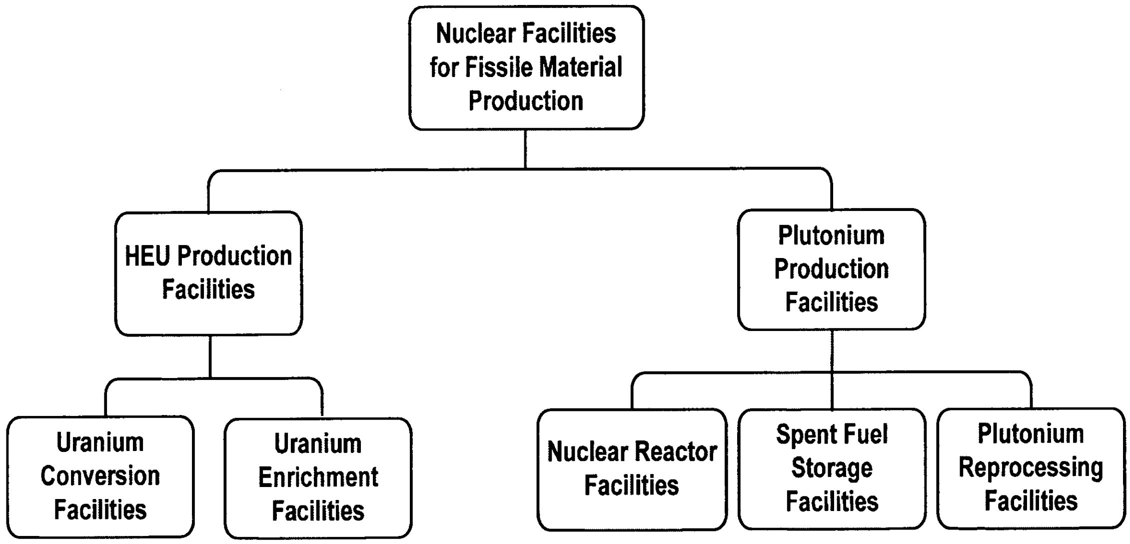


Figure 4.7 Nuclear Facilities Required for Nuclear Weapons Development Program

4.6.1 Facilities for Uranium Enrichment

Two kinds of facilities are required in order to produce Weapons-Grade Uranium (WGU): Uranium Conversion Facilities (UCFs) and Uranium Enrichment Facilities (UEFs). Most uranium enrichment technologies operate on a gaseous form of uranium, i.e., UF6. UCFs are used to convert yellow cake (U_3O_8), which is the form of uranium after a milling process, into UF_6. The gaseous product of uranium from uranium conversion facilities is enriched to the level that the proliferators desire. Gaseous Diffusion Plants (GDPs) and Gas Centrifuge Enrichment Plants (GCEPs) are the most common technologies; however, GCEPs are replacing gaseous diffusion plants.[124] If proliferators chose gas centrifuge technology for uranium enrichment, the construction of gas centrifuge manufacturing facilities would provide a high level of flexibility for diverting declared facilities and constructing clandestine GCEPs.

4.6.2. Facilities for Plutonium Reprocessing

Three kinds of facilities are required if proliferators want to build nuclear weapons based on plutonium material: reactor facilities, spent fuel storage facilities, and reprocessing facilities. First, Plutonium

[124] Orpet Peixoto and Laercio Vinhas, "Information Protection When Applying Safeguards to Centrifuge Enrichment Facilities," (Rio de Janeiro: Brazilian Argentine Agency for Accounting and Control of Nuclear Materials (ABACC), 2004).

does not occur naturally and has to be made through the neutron bombardment of U-238 in nuclear reactors. U-238 undergoes a nuclear reaction, and produces Pu-239, which is the main fissile material among plutonium isotopes as shown in Figure 4.8. Second, after uranium fuels are irradiated in nuclear reactor facilities, they need to be stored until the decay heat and radiotoxicity of the spent fuel is removed. Facilities for this process are called spent fuel storage facilities. Third, reprocessing facilities are required, which are normally designed to recycle plutonium in spent fuels such as MOX fuel.

4.7 Production of Fissile Materials

The next step following nuclear facility construction is the production of fissile material from constructed facilities. Throughout the entire process of a nuclear weapons program, the acquisition of HEU or separated plutonium is generally considered to be the most difficult. Even if nuclear facilities are constructed, a certain degree of technological know-how is required for proliferators to successfully or efficiently operate the facilities. Pathways for producing HEU and Weapons-Grade Pu differ considerably. In this chapter, only Pu-239 production will be reviewed. Figure 4.8 shows the radiochemical equations for the production of fissile material through the irradiation process. Pu-239 is produced by bombarding U-238 with neutrons in reactor facilities. Also, U-233 can be produced in a nuclear reactor by irradiating Th-232, Np-237, and Am-241 can also be produced in a nuclear reactor.

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}Np + ^{0}_{-1}e$$
$$\downarrow$$
$$^{239}_{92}Np \rightarrow ^{239}_{94}Pu + ^{0}_{-1}e$$

(a) Pu-239 production

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U + \gamma$$
$$\downarrow$$
$$^{236}_{92}U + ^{1}_{0}n \rightarrow ^{237}_{92}U \rightarrow ^{237}_{93}Np + ^{0}_{-1}e$$

(b) Np-237 production

$$^{232}_{90}Th + ^{1}_{0}n \rightarrow ^{233}_{90}Th \rightarrow ^{233}_{91}Pa + ^{0}_{-1}e \rightarrow ^{233}_{92}U + ^{0}_{-1}e$$

(c) U-233 production

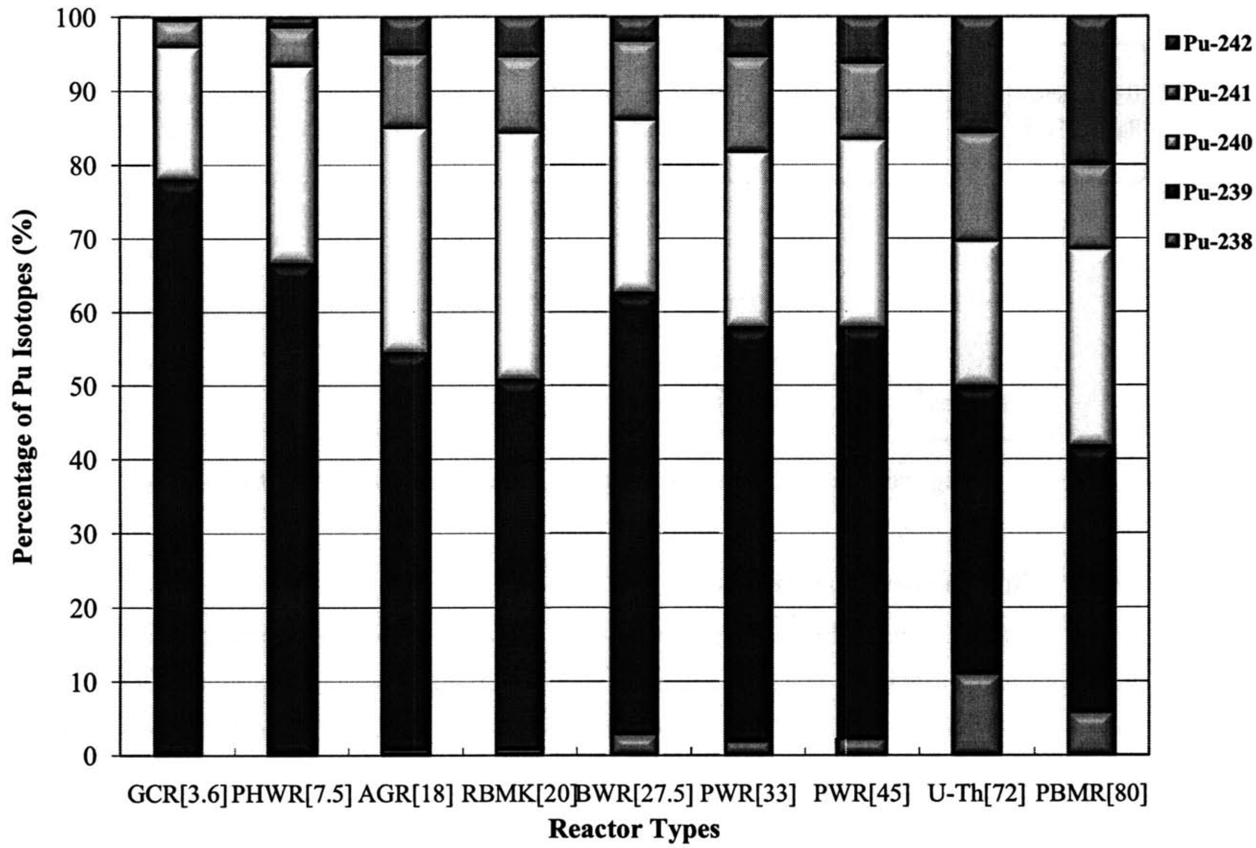
$$^{239}_{94}Pu + ^{1}_{0}n \rightarrow ^{240}_{94}Pu + ^{1}_{0}n \rightarrow ^{241}_{94}Pu \rightarrow ^{241}_{95}Am + ^{0}_{-1}e$$

(d) Am-241 production

Figure 4.8 Production of Various Fissile Materials

A variety of nuclear reactors exist for numerous applications and all of these reactors can produce Pu-239. Figure 4.9 shows how much of each plutonium isotope can be produced in different types of nuclear reactors, including Gas-Cooled Reactor (GCR), Advanced Gas-Cooled Reactor (AGR), Pressurized Heavy Water Reactor (PHWR) or Canada Deuterium Uranium (CANDU), Boiling Water

Reactor (BWR), Pressurized Water Reactor (PWR), and Pebble Bed Modular Reactor (PBMR). The figure below shows the plutonium production rates for each type of reactor when their design burn-up is achieved. Generally, reactors designed for low-burnup of uranium fuel produce a higher grade of plutonium for manufacturing weapons.



Note: Numbers in parentheses are burn-ups for each type of reactor.

Figure 4.9 Compositions of Plutonium from Different Reactors[125]

Figure 4.10 shows the trade-offs between the increase in the quantity of the plutonium isotopes and the increase in the grade of the plutonium-containing materials. As burnup time increases, the quantity of plutonium increases at the expense of plutonium quality. It is typical to use low-burnup reactor types or to operate for short-duration in reactors with high-burnup. The latter is the case with North Korea, which used a graphite moderated reactor for plutonium production.

[125] PBMR from J.S. Herring and P.E. MacDonald, "Characteristics of Mixed Thorium-Uranium Dioxide High Burnup Fuel" (paper presented at the ANS 1999 Annual Meeting, June 6-10 1999). and other reactors from Table I. Typical Isotopic Compositions of Spent Fuel at Discharge from Power Reactors in John Carlson et al., "Plutonium Isotopics - Non-Proliferation and Safeguards Issues" (paper presented at the IAEA Symposium on International Safeguards, Vienna, Austria, Oct. 13-17 1997).

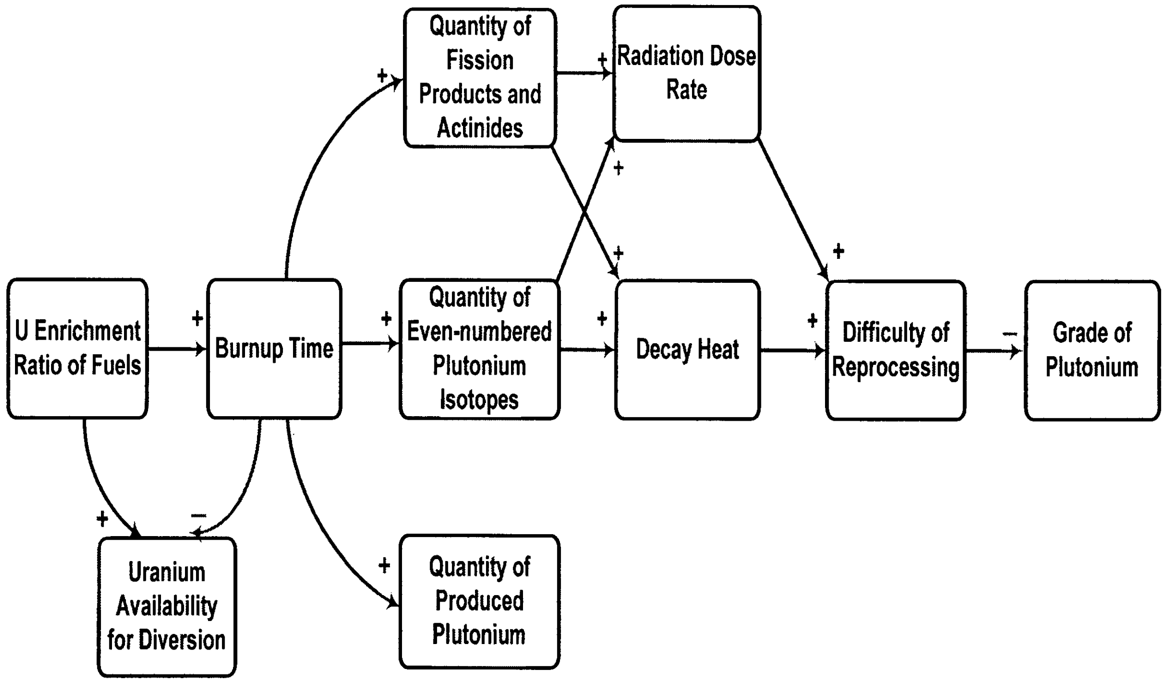


Figure 4.10 Fuel Burnup and Its Impact to Other Attributes[126]

4.7.3 Tritium (fusion material)

Tritium is used in a fusion-boosted weapon as well as in a thermonuclear weapon to boost its nuclear explosive yield. In both designs, tritium fuses with deuterium to create more high energy neutrons. However, the tritium must be replenished regularly because it has a half-life of only 12 years. Tritium is contained in all modern nuclear warheads. Because it does not occur in nature except in unretrievable traces, it must be produced artificially.[127] It is not possible to use renounce the use of tritium for warheads, because this would require new warhead designs and the need of nuclear testing.

The natural origin of tritium is in the upper atmosphere of the earth from atmospheric nitrogen or oxygen by bombardment with cosmic ray neutrons or solar photons. Tritium has been commonly produced in nuclear reactors by bombarding lithium 6 with neutrons. Tritium can also be extracted from irradiated heavy water that has been used to moderate or cool certain types of reactors. In this case, tritium is produced by neutron irradiation of deuterium, which is a hydrogen isotope that contains one proton and one neutron. Tritium is recovered from nuclear power plants and can be enriched through further processes, including water electrolysis, water distillation, thermal diffusion, permeation through membranes, as well as adsorption and chromatography. Tritium can be also produced using IR laser-

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[126] Taeshin Kwak, "Development of Proliferation Resistance for Nuclear Reactors (Term Paper for 22.251: System Analysis of the Nuclear Fuel Cycle)," (MIT, 2007).

[127] Annette Schaper, "Verification of a Fissile Material Cut-Off Treaty," *Disarmament Forum* 2 (1999).; M. Kalinowski and L. Colschen, "International Control on Tritium to Prevent Its Horizontal Proliferation and to Foster Nuclear Disarmament," *Science and Global Security, The Technical Basis for Arms Control, Disarmament, and Nonproliferation Initiatives* 5, no. 2 (1994/95)..

induced multiphoton dissociation (IRMPD) from Halogenated Methanes, Halogenated Ethanes, and Halogenated Propanes. [128] Table 4.6 shows the sources of tritium, including both natural and artificial sources.

Table 4.6 Sources of Tritium [Gheorge Văsaru, 1993]

Sources		**Chemical reactions**
Natural	**Upper atmosphere**	• Neutron bombardment - $^{14}N + n \rightarrow T + {}^{12}C$ - 4.3 MeV - $^{16}O + n \rightarrow T$ + 14C
Artificial	**Thermonuclear detonations**	• Residues of nuclear weapons test - $D + D \rightarrow T + H$ + 4.03 MeV - $^{6}Li + n \rightarrow T + {}^{4}He$ + 4.69 MeV
	Fission nuclear reactors (LWR and HWR)	• Nuclear reactions with thermal neutrons (in coolant water) - $D + n \rightarrow T$ + gamma + 6.26 MeV - $^{6}Li + n \rightarrow T + {}^{4}He$ + 4.69 MeV (lithium impurities of the fuel rods from the primary coolants or from graphite rods) • Nuclear reactions with fast neutrons in ^{10}B(from control rods) or in ^{14}N (from residual gas) - $^{10}B + n \rightarrow T + {}^{2}He$ - $^{14}N + n \rightarrow T + {}^{12}C$ - 4.3 MeV • Activation reaction of deuterium (natural concentration is 0.015%) and the reaction of hydrogen from ordinary water - $H + n \rightarrow D + n \rightarrow T + \gamma$ + 6.26 MeV
	Fusion nuclear reactors	• D-D reactions - $D + D \rightarrow T$ (1.01 MeV) + H (3.02 MeV)

4.8 Nuclear Weapons Manufacturing

In order to manufacture nuclear weapons, detailed weapon designs as well as both non-nuclear materials,[129] and manufacturing equipment (i.e., industrial furnaces) are required in addition to the preparation of fissile material. [130] Furthermore, detailed technical know-how, including component fabrication information, and assembly instructions is required for the manufacture of nuclear weapons. Human resources required at this step include a nuclear physicist or engineer, skilled machinists, explosives experts, and electronics personnel. Industrial infrastructure is also necessary. Another

[128]George Văsaru, *Tritium Isotope Separation* (Boca Raton, FL: CRC Press Inc., 1993).
[129]Beryllium, polonium-210, tritium and gallium belong to this category and these materials have dual-use purposes.
[130]Carlson and Leslie, "Safeguards Intensity as a Function of Safeguards Status".

important factor that warrants consideration is the development of ***nuclear-capable delivery systems***, coupled with the miniaturization of nuclear warheads. However, delivery systems for nuclear warheads are not considered in this study.

Generally, the manufacture of nuclear weapons is divided into two parts: shaping of fissile material and manufacture of implosion devices. The step of nuclear weapon manufacture begins with the acquisition of dual-use items such as high-explosive lenses, high-energy electrical components, high-flux neutron generators, and specialized casting and machining equipment. Manufacture of fissile material for nuclear warheads includes conversion of fissile material into ***metallic form (pure uranium)***, and casting and machining of fissile material into the shapes required for a weapon.

However, the acquisition of fissile materials does not pose a challenge. Since the infrastructure of nuclear weapons design from 30-50 years ago is considered obsolete,[131] such information is readily available to nuclear weapon developers. Technology developments in other industries have also helped to increase the availability of this technology.

4.9 Nuclear Weapons Test

4.9.1 Objectives of Nuclear Test

US DOD's MCTL provides a broad definition of ***nuclear testing*** as tests that encompass all experiments where special fissionable material is placed in contact with high chemical explosives, which are then detonated with an ignition propellant. In order to complete a nuclear weapons program, calculations, laboratory experiments, and field testing of all the components are necessary. However, prototype nuclear weapons could be manufactured prior to a full-yield test [See Appendix B].

The objectives of nuclear tests include the development of new nuclear weapons, understanding the effects of nuclear explosions, the verification of the reliability and safety of deployed nuclear weapons[132], and the development of nuclear explosions for peaceful purposes.

Nuclear Explosion Tests were generally carried out with the following purposes:

- Development of new models of nuclear weapons[133]
- Verification of functionality of Stockpile Weapons (weapon health)[134],
- Production verification of a developed design,
- Development of Peaceful Nuclear Explosives (PNEs), and

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[131] Richard Garwin and Simonenko Vadim, "Nuclear Weapon Development without Nuclear Testing?" (paper presented at the The Pugwash Workshop on Problems in Achieving a Nuclear-Weapon-Free World, London, England, Oct. 25-27 1996).

[132] This is related to the possible deterioration of weapons and their vulnerability to the effects of explosions.

[133] R.S. Norris, "French and Chinese Nuclear Weapon Testing," *Security Dialogue* 27, no. 1 (1996).

[134] To detect deterioration not visible on static radiographs, some of the pits taken at random from the stockpile can be cut open and their condition inspected by microscope. S.D. Drell and Bob Peurifoy, "Technical Issues of a Nuclear Test Ban," *Annual Review of Nuclear and Particle Sciences* 44, no. 44 (1994).

•Study of weapon effects[135]

In the case of new nuclear weapons development, modeling itself is not enough to guarantee accurate prediction of nuclear explosive yield. Politically, a certain proliferator who hopes to demonstrate its technical prowess may therefore elect to pursue nuclear testing.

Nuclear testing can be divided into three types: hydrodynamic, hydronuclear, and nuclear explosive yield testing. To conduct nuclear tests, test sites, technical know-how such as nuclear explosive yield data and simulation laboratories equipped with supercomputers are required. Hydrodynamic nuclear testing is permitted under the CTBT while hydronuclear testing and nuclear explosive yield testing are not. For hydronuclear testing, the yields that are generally achieved range from much less than 1 kg TNT equivalent to many tons. A methodology to verify the occurrence of nuclear explosive yield test is detailed in Chapter 8.

4.9.2 Cases of Non-Testing

A proliferator may not require full-yield nuclear testing for the completion of its nuclear weapons program. It is possible to build simple nuclear weapons without a nuclear explosion test. This would depend on the nature of the weapon as well as the prior experience, technical capabilities, and the degree of assurance of the proliferators. Some types of nuclear weapons like a Hiroshima-type bomb can be built and deployed without any kind of yield test, and a proliferator could have reasonable confidence in the performance of such a device.

Experts still differ with regard to the degree of limitations that the absence of tests imposes on bomb design and the level of weapons sophistication. [136] There will be always a nagging doubt as to whether or how well newly-developed weapons will perform. Without nuclear tests of substantial yield, it is difficult to build compact and light fission weapons and essentially impossible to have any confidence in the design of a boosted or thermonuclear weapon. If there is no a full-yield nuclear test, then great care must be given to the non-nuclear experiments with high-capacity computers, including the demonstration of the behavior of the non-nuclear components including the firing set, detonators, and neutron generators. Table 4.7 lists cases where nuclear weapons tests may not be required.

[135] The United States typically tested six times in the development of each new model of nuclear weapon, while France is said to have used some 22 per model.
[136] Avner Cohen and Benjamin Frankel, *Opaque Nuclear Proliferation* (Frank Cass and Company Ltd., 1991).

Table 4.7 Cases that Do Not Require Nuclear Weapons Tests

Cases	Background
WGU-based bombs	A nuclear bomb with weapons-grade uranium is highly trustable, thereby not requiring weapons tests. For example, gun-type design weapons such as "Little Boy" and South African nuclear bombs had not gone through tests.
Nuclear weapon with a certified design	A full-yield nuclear test is unnecessary if a design is already certified by previous tests. [137]
Acquisition of nuclear weapons	Either if the devices were stolen or if the weapon were "legitimately" acquired from a nuclear power, presumably use control information would be passed on to purchaser.
No confirm or no denial (NCND)	Some countries want to keep a secret of nuclear weapons development like the case of Israel

4.10 Time Required for Nuclear Weapons Program

The estimate on the time requirement for the successful completion of a nuclear weapons program is one of the debatable questions in the study of nuclear nonproliferation. Obtaining information about the pattern of a nuclear weapons program is essential to establishing effective nonproliferation policies. Meyer (1986) defines ***Lag time*** as the amount of time a given country requires after the proliferation decision to produce its first nuclear weapon. The shorter the lag time, the higher the risk of going nuclear.[138] However, it should be noted that lag time is significantly dependent on a latent capacity of a state.

Leonard Spector (1994) argues that states typically take ten years to develop nuclear weapons.[139] He argues that states that have sought nuclear weapons generally have required at least a decade and refers to this pattern as the "***Ten Year Rule***." As shown in Figure, current NWS developed their nuclear weapons in less than five years; however, a decade or more has been required for developing countries. The MCTL[140] estimates that new proliferators with First-world technological bases can probably build their pure nuclear fission design weapons three to five years after making a political decision to do so, including nuclear facility construction and nuclear material acquisition,

[137] Frank Barnaby, *How Nuclear Weapons Spread: Nuclear-Weapon Proliferation in the 1990s* (New York, NY: Routledge, 1993)., p.47.
[138] For more information, see Stephen M. Meyer, *The Dynamics of Nuclear Proliferation* (Chicago, IL: University of Chicago Press, 1984)., pp.149-153.
[139] Leonard S. Spector, "Strategic Warning and New Nuclear States," *Defense Intelligence Journal* 3, no. 1 (Spring 1994).
[140] U.S. Department of Defense, "Militarily Critical Technologies List (MCTL), Part II: Weapons of Mass Destruction Technologies, Section 5-Nuclear Weapons Technology."

under the assumption that finances and resources are available. Three to ten more years may be additionally required to develop nuclear weapons of an advanced design. [141]

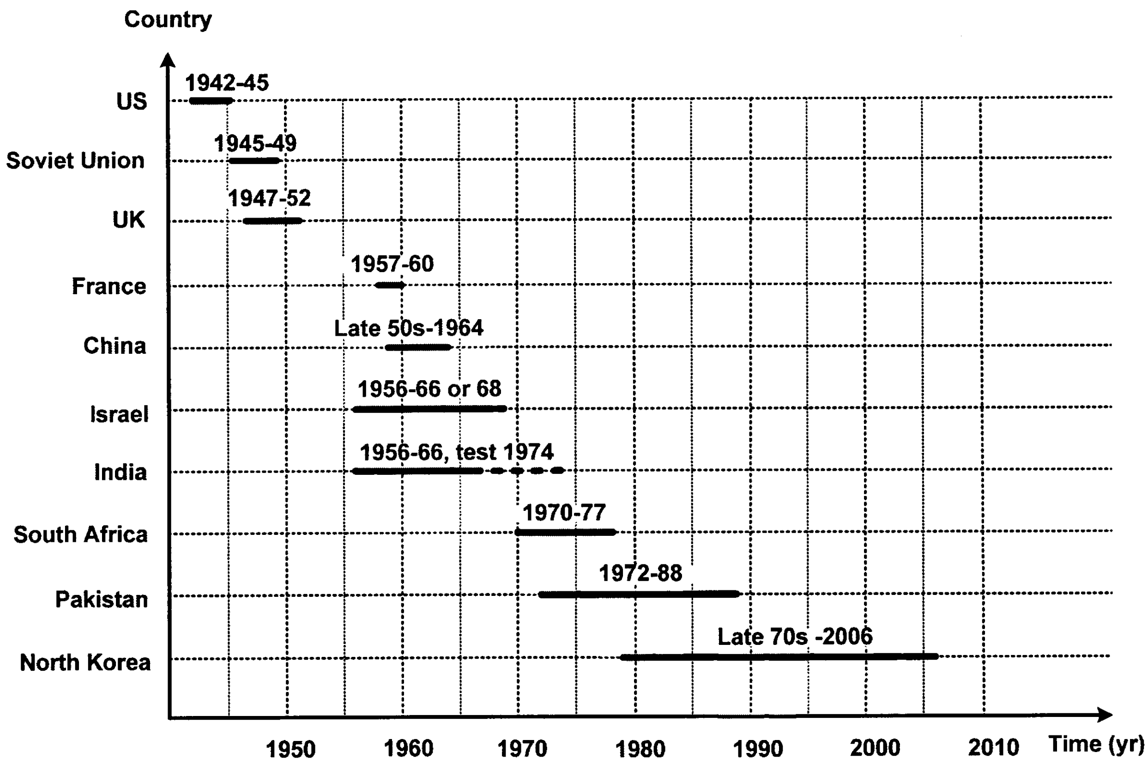

Figure 4.11 Time Spent for Completion of Nuclear Weapons Program[142]

4.11 Summary

The overall process of a nuclear weapons program was reviewed in this chapter. A nuclear weapons program is very complex and requires an extensive and a high level of capabilities whether they are intrinsic or extrinsic. The process of nuclear weapons program explained in this Chapter does not need to be sequential because each step of nuclear weapons program can proceed in parallel. Table 4.8 summarizes what components are produced and what capabilities are required at each stage of a nuclear weapons program, after the decision is made to "go-nuclear" by national leaders. In order for a nuclear weapons program to be successfully, nuclear material, equipment for facilities and weapons manufacture, and human resources (i.e., technical know-how) should be prepared and well-combined.

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[141] Robert Bledsoe, "Laser Isotope Enrichment: A New Dimension to the Nth Country Problem?," *Air University Review* (March-April 1978). He argued that it would take five to ten years when the decision is made to nuclear weapons. Two to three years to plan, design and construct conventional enrichment facilities; and an additional two to three years for material production and weapon assembly.

[142] Time spent refers to a time from the go-nuclear decision to the successful test of its first nuclear device. Spector, "Strategic Warning and New Nuclear States."

Table 4.8 Components and Steps of Nuclear Weapons Program

Step	Procedure	Components
1	National leader's decision	• Environment and capabilities
2	Human resource build-up	• Nuclear engineers and scientists • Technical know-how acquisition • Research reactor construction
3	Construction of fissile material acquisition facilities	For HEU production • Uranium Conversion Facility (UCF) • Uranium Enrichment Facility (UEF) • Gas centrifuge manufacture facility For WGPu production • Reactor facilities • Spent fuel storage facilities • Plutonium Reprocessing Facility (PRF)
4	Fissile material acquisition	• Significant quantity of fissile material: U-235, Pu-239, Np-239, and Am-241 • Tritium for weapons of advanced designs
5	Nuclear weapons manufacturing	• Nuclear warhead design • Manufacturing facilities • Delivery systems
6	Nuclear bomb tests	• Test equipment preparation • Simulation and non-nuclear test • Test site preparation

CHAPTER 5 THE NUCLEAR NONPROLIFERATION TREATY REGIME

5.1 Introduction

A number of institutional and non-institutional frameworks have been proposed to deal with nuclear proliferation issues since the Treaty on the Nonproliferation of Nuclear Weapons (NPT) went into force in 1970. This framework is often referred to as the nuclear nonproliferation regime or the NPT regime. Yet, there are disputes about whether or not the NPT regime has been successful because several countries have proliferated despite the existence of the NPT regime. However, it should be noted that no international regimes can be perfect in achieving the objectives in specific issue areas; therefore, theoretical tools to describe how successful the NPT regime has been are necessary to clarify disputes.

This Chapter provides the fundamental framework in understanding and analyzing the nuclear nonproliferation regime. The final objective of this chapter is to develop a tool to analyze the power and the effectiveness of the nuclear nonproliferation regime. This Chapter is divided into two parts. The first part of this Chapter is devoted to examining regime theory such as regime concept, regime effects, regime effectiveness and regime power. The second part offers a comprehensive analysis on the nuclear nonproliferation regime based on regime theory. As a result, quantitative as well as qualitative ways of describing the power and the effectiveness of the NPT regime will be obtained.

5.2 International Regimes in International Relations Theory

5.2.1 Regime Theory in Liberalism and Realism

The study on regime theory can be divided into three categories:[143]the objectives of regime formation and the functions, maintenance and disappearance of regimes; classification of regime types by features; and consequences or effects of regimes (evaluation of regimes' success and quantitative methodology to measure effectiveness of regimes).[144] Theories of international regimes can be classified as realism, neoliberalism, and constructivism. These approaches differ over the nature of international cooperation and the degree to which international institutions play a role. Liberalists believe that cooperation comes about through a convergence of state interests, and that international institutions help create the synthesis of interests. One related school in liberalism, ***liberal institutionalism***, argues that regimes

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[143] Chan-Kyu Kim, "A Study on the Nuclear Non-Proliferation Regime" (Dongguk University, 2000). p.40.

[144] Helm and Sprinz define regime effects as improvements in the object of evaluation that can be attributed to the regime. Carsten Helm and Detlef Sprinz, "Measuring the Effectiveness of International Environmental Regimes," *The Journal of Conflict Resolution* 44, no. 5 (Oct. 2000). Krasner also assumes the set of causal relationships between basic causal variables (powers and interests) and their related behavior and outcomes though regimes, which could be conceived of as intervening variables. Stephen Krasner, "Structural Causes and Regime Consequences: Regimes as Intervening Variable," *International Organization* 36, no. 2 (Spring 1982).

affect the behavior of states under the assumption that international cooperation among states is possible in the anarchic system.

On the contrary, realists attempt to explain regimes based on the relationship of power using ***hegemonic stability theory***. From the viewpoint of realism, international regimes are the products of existing power relationships that reflect the relative power distribution of states in the international system. In other words, realists argue that the presence of a strong hegemony is the factor that makes regimes successful and features of regimes change along with the balance of bargaining power among the states that negotiate the establishment of new regimes.

5.2.2 Concept of International Regimes

The concept of regimes varies over their roles and relative contexts between international regimes and international organizations or international institutions. Keohane (1989) defines ***international institutions*** as ones that include international organizations, international regimes, and conventions.[145] Kratochwil and Ruggie (1986) define international regimes as informal ordering mechanisms, whereas ***international organizations*** are concrete entities. They suggest that international organizations can contribute to the effectiveness of international regimes. Various definitions of regimes proposed by international relations scholars are summarized in Table 5.1.

Table 5.1 Definitions of Regime by Different Scholars

Scholar	Definition
Keohane and Nye (1977)[146]	"*Sets of governing arrangements*" that include networks of rules, norms, and procedures that regularize behavior and control its effects.
Haas (1980)[147]	*A mutually coherent set of procedures, rules, and norms.*
Young (1980)[148]	*Social institutions* governing the actions of those interested in specifiable activities (or meaningful sets of activities).
Krasner (1983)[149]	*Principles, norms, rules and decision-making procedures around which actor expectations converge in a given issue-area.*

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145 Robert Keohane, *International Institutions and State Power: Essays in International Relations Theory* (Boulder, CO: Westview Press, 1989). p.2.

146 Robert Keohane and Joseph Nye, *Power and Interdependence* (Boston, MA: Little, Brown, and Company 1977). p.19.

147 Ernst B. Haas, "Technological Self-Reliance for Latin America: The OAS Contribution," *International Organization* 34, no. 4 (Autumn 1980).

148 Oran Young, "International Regimes: Problems of Concept Formation," *World Politics* 32, no. 3 (April 1980).

149 Krasner, "Structural Causes and Regime Consequences: Regimes as Intervening Variable."

(Continued)

Keohane (1988)[150]	*Specific institutions* involving states and/or transnational actors, which particular issues in international relations.
Tate (1990)[151]	*An authoritative arrangement* among international actors (states) that facilitates the accomplishment of specific goals through a process involving coordination or expectations and modification of certain behavioral patterns.
Kratochwil and Ruggie (1986)[152]	*Governing arrangements* constructed by states to coordinate their expectations and organize aspects of international behavior in various issue-areas.

5.3 Regime Effects

5.3.1 Concepts of Regime Effects

The most fundamental issue in regime theory is the question of whether regimes make any difference in the behavior of participating states, i.e., effects of regimes. ***Regime effects*** can be defined as the improvements in the object of evaluation that can be attributed to regimes.[153] Krasner (1982) explores the significance of regimes in impacting related behavior and outcomes via the ***mechanism approach***, in other words, introducing basic causal variables and intervening variables. Basic variables are further classified as exogenous variables and non-exogenous variables. Exogenous variables such as state interests and state power are treated as important variables that can generate regimes on their own. In contrast, regimes are assumed to be intervening variables between basic variables and the outcomes of regimes. Figure 5.1 shows four different approaches Krasner summarized (1982) regarding the issue of regime significance as follows: (a) The Realist sees power resources as the sole and decisive variable, whereas an international regime is an intervening and non-independent variable; (b) The Modified structuralist (or neorealist) suggests that regimes may matter, but only under fairly restrictive conditions; (c) The Grotian sees regimes are fairly effective;[154] and (d) considering feedback, regimes can be conceived in a fourth manner as autonomous variables independently affecting related behavior and outcomes as well as basic causal variables.[155]

[150] Robert Keohane, "International Institutions: Two Approaches," *International Studies Quarterly* 32, no. 4 (1988).
[151] Trevor McMorris Tate, "Regime-Building in the Non-Proliferation System," *Journal of Peace Research* 27, no. 4 (Nov. 1990).
[152] Friedrich Kratochwil and John Ruggie, "International Organization: The State of the Art on the Art of the State," *International Organization* 40, no. 4 (Autumn 1986).
[153] Helm and Sprinz, "Measuring the Effectiveness of International Environmental Regimes."
[154] Stephen D. Krasner, "Regimes and the Limits of Realism: Regimes as Autonomous Variables," *International Organization* 36, no. 2, International Regimes (Spring 1982).The basic causal variables he suggests include egoistic self-interest, political power, norms and principles, usage and custom, and knowledge.
[155] Ibid.

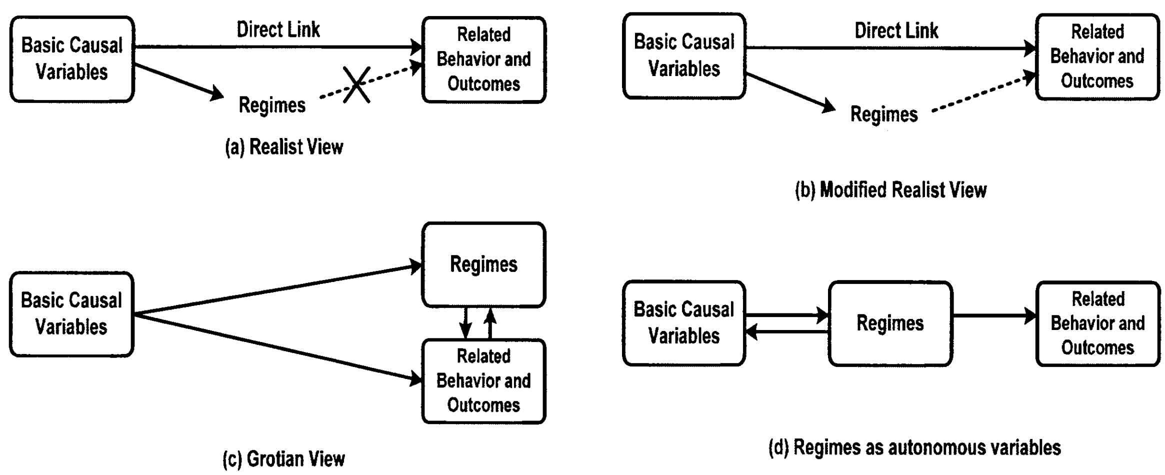

Figure 5.1 Different Views on Regime Effects

5.3.2. Measurement of Regime Effects

Helm and Sprinz (2000) define ***regime effects*** as improvements in the object of evaluation that can be attributed to the regime.[156] Similarly, Mitchell (2004) defines regime effects as changes that are best explained by the regime and cannot be explained by other factors. Regime effects encompass intended and unintended, direct and indirect, and desirable and undesirable effects. In contrast, regime effectiveness includes only intended and direct effects.[157] Levy et al. (1993) propose the concept of ***three Cs*** for measuring regimes effects.[158] Three Cs include level of ***concern*** (do states care about the problem?), ***contractual*** environment (Can they strike profitable bargains?) and state ***capacity*** (Can they implement what they agree to?). Weiss (1999) suggests the concept of ***compliance*** in order evaluate regime effects. [159] He defines ***compliance*** as a matter of whether and to what extent countries do adhere to the provisions of the accord, which includes ***implementation*** and ***enforcement.*** He uses compliance as a means to measure the degree to which the actors whose behavior is targeted by the agreement conform to the implementing measures and obligations.

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[156] Helm and Sprinz, "Measuring the Effectiveness of International Environmental Regimes."

[157] Ronald B. Mitchell, "Chapter 6. A Quantitative Approach to Evaluating International Environmental Regimes," in *Regime Consequences* ed. Arild Underdal and Oran R. Young (Dordrecht, Netherlands: Kluwer Academic Publishers, 2004)., p.124.

[158] M.A. Levy, R.O. Keohane, and P.M. Hass, "Improving the Effectiveness of International Environmental Institutions," in *Institutions for the Earth: Sources of Effective International Environmental Protection*, ed. P.M. Haas, R.O. Keohane, and M.A. Levy (Cambridge, MA: MIT Press, 1993)., pp. 397-426.

[159] E. Brown Weiss, "Understanding Compliance with International Environmental Agreements: The Baker's Dozen Myths," *University of Richmond Law Review* 32 (1999). For more discussion about the definitions, see United Nations Environment Programme (UNEP), "Comparative Analysis of Compliance Mechanisms: Under Selected Multilateral Environmental Agreements," (Nairobi: Dec. 2005).

5.4 Regime Effectiveness

5.4.1. Concepts of Regime Effectiveness

Victor et al. (1998) define ***regime effectiveness*** as a measurement of *"the degree to which international agreement lead to changes in participating members' behavior that helps to solve specific problems."*[160] Young and Levy (1998) define regime effectiveness as "*a matter of the regime's contributions that institutions make to solving the problems that motivate actors to invest the time and energy needed to create them.*" Yet, the meaning of effectiveness can significantly vary depending on approaches used: problem-solving, legal (compliance), economic (economic efficiency), normative (fairness or justice, stewardship, participation, and so on), and political.[161] In general, regime effectiveness is regarded as a concept to evaluate regime effects using quantitative methodology.[162]

5.4.2 Measurement of Regime Effectiveness

The quantification of regime effects is not an easy task because cases for carrying out quantitative analysis on the performance of regimes are both limited in number and sometimes difficult to draw clear conclusions from. Most work using a quantitative approach to evaluating international regimes has been done in the study of international environmental regimes.[163] Stokke (2004) uses Qualitative Comparative Analysis (QCA) to explain regime effectiveness in a qualitative way.[164] He proposes the use of causal processes, or mechanisms for analyzing regime effectiveness: the mechanism of shaming rather than reward to connect regimes and problem-relevant behavior with some Boolean expressions.

Quantitative analysis has been done to analyze some aspects of effects where a qualitative analysis approach does not work well. Those aspects include (i) comparison of effectiveness between sanctions and rewards, (ii) under what conditions one is more effective than other, (iii) what kinds of problems are easier to resolve, etc. Helm and Sprinz (2000) developed a general measurement concept for assessing the degree to which international environmental regimes contribute to environmental problem-solving by introducing the concepts of non-regime counterfactual (NR), collective optimum (CO), and actual performance (AP). ***Effectiveness scores*** (E) can be calculated using the equation

$$E = \frac{AP - NR}{CO - NR} \qquad (5.1)$$

[160] D. G. Victor, K. Raustiala, and E.B. Skolnikoff, *The Implementation and Effectiveness of International Environmental Commitments: Theory and Practice* (Cambridge, MA: MIT Press, 1998)., p.460.
[161] Oran R. Young and Marc A. Levy, "Chapter 1. The Effectiveness of International Environmental Regimes," in *The Effectiveness of International Regimes*, ed. Oran R. Young (Cambridge, MA: MIT Press)., pp.3-6.
[162] Helm and Sprinz, "Measuring the Effectiveness of International Environmental Regimes."
[163] For more information, see Mitchell, "Chapter 6. A Quantitative Approach to Evaluating International Environmental Regimes.", pp.121.
[164] Olav Schram Stokke, "Chapter 5. Boolean Analysis, Mechanisms, and the Study of Regime Effectiveness," in *Regime Consequences*, ed. Arild Underdal and Oran. R. Young (Dordrecht, Netherlands: Kluwer Academic Publishers, 2004)., pp.87-120.

where

•Non-Regime Counterfactual (NR)

The value when none of the instruments used to solve the problem can be ascribed to the international regime. This is the lower bound of problem-solving capacity of the regime.

•Collective Optimum (CO)

This is the point where the marginal collective costs of using the policy instrument equate to the collective benefits. This the upper bound of problem-solving capacity of the regime.

•Actual Performance (AP)

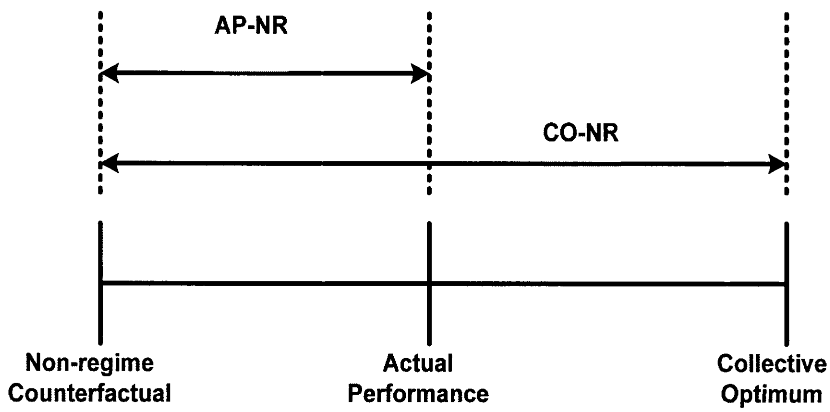

Figure 5.2 Measuring Regime Effectiveness

The effectiveness of regime is given as the relative distance that the AP has moved from the NR toward the CO or as the percentage of the regime potential has been achieved. (The ***regime potential*** is the distance between NR and CO).[165] This value falls strictly into the interval [0, 1].

5.5 The Power of International Regimes

5.5.1 Conceptual Framework

The concept of power is fundamental to explain what regimes can or cannot do in terms of achieving the goals set by regimes. It seems that there has been no study on how to evaluate the power of regime. Some research about the power of states has been done to measure the relative power of states. This could be applicable to evaluating the power of regime. RAND (2005) proposes three levels in measuring the power of states: resources or capabilities, or power-in-being, conversion of resources or

[165] Helm and Sprinz, "Measuring the Effectiveness of International Environmental Regimes."

capabilities through national processes, and power in outcomes.[166] According to the report, the power of states is the converted product of resources or capabilities of states. However, resources and capabilities of states are not distinguished in the report. And it acknowledges that measuring state power is the most elusive among three levels.

A. Resource-based Model

It will be absolutely more elusive if one wants to measure the power of international organizations or international regimes rather than that of states. A ***resource-based model*** in management science may be useful for describing the power of organizations. The model introduces resources and capabilities to explain the competence of organizations. Oden (1999)[167] distinguishes resources from capabilities as follows: ***resources*** are "inputs into a firm's production process such as capital, equipment, skills of individual employees, finance and talented managers.", whereas a ***capability*** is "the capacity for a set of resources to integratively perform a task or activity to achieve a desired end state." Based on these definitions, the resource-based theory assumes that each organization is ***a collection of unique resources and capabilities*** that provides the basis for its strategy and is the primary source of its returns.[168]

B. Organizational Capability

Ulrich and Wiersema (1989)[169] propose the concept of "***organizational capability***", which is defined as "*an organization's ability to establish internal structures and processes that create organization-specific competencies and enable it to adapt to changing external pressures.*" Sparrow and Braun (2007) also introduce organizational capability and define it as "*a capacity to deploy resources for a desired end result of organizations.*"[170]

Based on the previous discussion with regard to the power of international regimes, resources and capabilities will be employed in this study in order to describe the power of international regimes.

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[166] Gregory F. Treverton and Seth G. Jones, "Measuring National Power," (Santa Monica, CA: RAND National Security Research Division, 2005).

[167] Howard W. Oden, *Transforming the Organization: A Socio-Technical Approach* (Westport, CT: Quorum Books, 1999)., pp.56-57. The relationship between resource or capabilities and state power in RAND report seems similar to the relationship between resources and capabilities in Oden's study.

[168] Michael A. Hitt, R. Duane Ireland, and Robert E. Hoskisson, *Strategic Management, Competitiveness and Globalization: Concepts and Cases*, 6th ed. (Mason, OH: Thomson, 2005)., pp.19-20.

[169] Davis Ulrich and Margarethe F. Wiersema, "Gaining Strategic and Organizational Capability in a Turbulent Business Environment," *The Academy of Management Executive* 3, no. 2 (May 1989). In the original context, a firm is used instead an organization but I modified it for the purpose of study.

[170] Paul R. Sparrow and Werner Braun, "Chapter 5. Human Resource Strategy in the International Context," in *Handbook of Research in International Human Resource Management*, ed. Michael M. Harris (Philadelphia, PA: Lawrence Erlbaum, 2007)., p.86.

5.5.2 Resources of International Regimes

Resources of international regimes can be directly derived from the concept of regime effects and they will include implementation, verification resources, and compliance-enforcement resources.

Implementation refers to the actions that governments take to translate international accords into domestic law and policy. In other words, implementation of international agreements means the legal implementation of international commitments into national law in the form of legislation or regulations, judicial decrees, or other actions. [171]However, the level of implementation may not be a direct indicator of how effectively it changes the behavior of target groups. Mazmanian and Sabatier (1981) identified three factors that affect the implementation process: tractability of the problems addressed by a statute; ability of statute to structure implementation; and non-statutory variables affecting implementation.[172] The last factor can be measured as the level of system infrastructure.

Compliance means conforming to a specification or policy, standard or law that has been clearly defined. [173] There are two types of approaches to compliance, an enforcement model of compliance and a managerial model of compliance; however, it seems that the former is best suited for the scope of the study. [174]

Enforcement refers to the actions that will be taken by international regimes once violations or non-compliance occur. Enforcement involves formal dispute settlements, procedures and penalties, sanctions, or other coercive measures to induce compliance with obligations.[175] The UNEP (2007) provides compliance mechanisms to be enforced that encompass performance information reviews, multilateral non-compliance procedures, non-compliance response measures, and dispute settlement procedures.[176]

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[171] H.K. Jacobson and E. Brown Weiss, "Strengthening Compliance with International Environmental Accords," *Global Governance* 1, no. 2 (1995).

[172]Paul A. Sabatier and Daniel A. Mazmanian, "Chapter 1. The Implementation of Public Policy: A Framework of Analysis," in *Effective Policy Implementation*, ed. Daniel A. Mazmanian and Paul A. Sabatier (Lexington, MA: Lexington Books, 1981). They propose six factors as non-statutory variables: socioeconomic conditions and technology, media attention to the problem, public support, attitudes and resources of constituency groups, support from sovereigns, and commitment and leadership skill of implementing officials, pp.6-7.

[173] For more discussion about a treaty of compliance, see Abram Chayes and Antonia Handler Chayes, *The New Sovereignty: Compliance with International Regulatory Agreements* (Cambridge, MA: Harvard University Press, 1995)., pp.1.-28.

[174] Abram Chayes et al., "Chapter 3. Managing Compliance: A Comprehensive Perspective," in *Engaging Countries: Strengthening Compliance with International Environmental Accords*, ed. Edith Weiss and Harold Jacobson (Cambridge, MA: The MIT Press, 2000)., pp.41-42.

[175] Weiss, "Understanding Compliance with International Environmental Agreements: The Baker's Dozen Myths."

[176] Dispute resolution procedures can be invoked in case of non-compliance by participating members to the regime. These procedures are composed of negotiation, conciliation, and binding arbitration and all of these procedures can be either voluntary or compulsory. United Nations Environment Programme (UNEP), "Comparative Analysis of Compliance Mechanisms: Under Selected Multilateral Environmental Agreements.", p.29-33. For more discussion on dispute settlement from legal perspective, see United Nations Environment Programme (UNEP), "Comparative Analysis of Compliance Mechanisms: Under Selected Multilateral Environmental Agreements.",pp.110-118; Math Noortmann, *Enforcing International Law: From Self-Help to Self-Contained Regimes* (Burlington, VT: Ashgate Publishing Co., 2005).

Verification is defined as "a mechanism or procedure to confirm that each state party to the agreement is acting in conformity with its obligations, and to detect those who violate their obligations."[177] Verification resources can enable international regimes to check whether or not the implementation process in participating states is going well.

The required amount and the type of verification resources may vary for different regimes. Thus, during the formation process of international regimes, verification features should be set up carefully.[178]In general, verification is merely considered as a technical issue; therefore, the technical community may regard the enhancement of technological capabilities as the main objective that the community can contribute. Yet, politics becomes a main player whenever some states are held in suspicion. In this regard, verification resources should be seen from both legal and technical aspects.

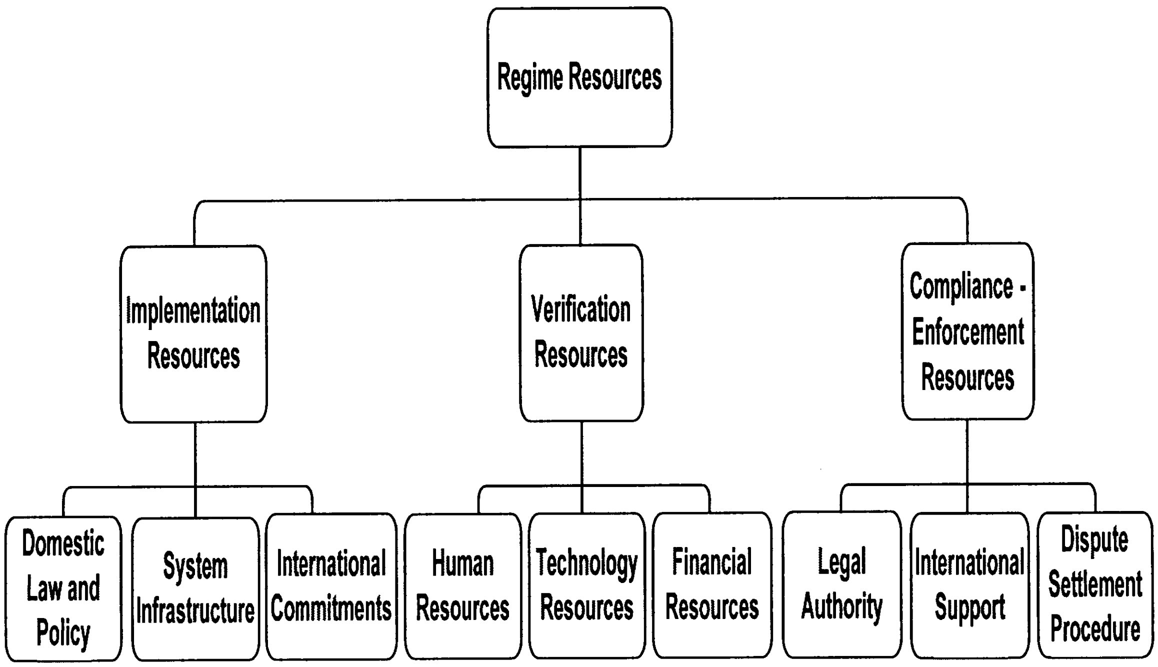

Figure 5.3 Resources of a Regime

5.5.3 Capabilities of International Regimes

It would be possible to convert the resources of international regimes in several ways. For the scope of this study, an international regime's capabilities are described from technical and political perspectives.

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[177] J. Christian Kessler, *Verifying Nonproliferation Treaties: Obligation, Process, and Sovereignty* (Washington D.C.: National Defense University Press, 1995).

[178]Negotiation for appropriate verification framework is done through bargaining, coercion, persuasion, coalition-building, and other political processes For more discussion about political aspects of verification, see Nancy W. Gallagher, *The Politics of Verification* (Baltimore, MD: The Johns Hopkins University Press, 1999)., pp.1-26.

Bell and Pavitt (1993) define technological capability as the resources needed to generate and manage technological change, which are accumulated and embodied in skills, knowledge, experience and organizational systems.[179] Marcelle (2007) suggests that ***technical capabilities*** are organizationally integrated capabilities of both embodied (held-in people) and non-embodied (a property of components) elements. These elements include skills, attitudes, knowledge, aptitudes, equipment, devices, machinery, and software. [180]

Martinez (1996) defines the ***legal capability of international organizations*** as the ability to enact binding decisions directly applicable on member states. [181] Following this classification, implementing and compliance-enforcing resources can translate into legal capabilities among regime resources. In contrast, verification resources can be projected as legal capabilities as well as technical capabilities.

5.6 Features of the Nuclear Nonproliferation Regime

A number of institutional and non-institutional frameworks have been proposed to deal with nuclear proliferation issues since the nuclear non-proliferation treaty (NPT) went into force. This framework is often referred to as the nuclear nonproliferation regime or the NPT regime, named after the NPT. The nuclear nonproliferation regime is one of international regimes, but it has unique features that differ from those of other international regimes.

A fundamental question might arise as to whether a set of international efforts toward nuclear nonproliferation can be defined as a regime. Brzoska (1992)[182] suggests that it is normal to speak of a "nuclear nonproliferation regime" because international regimes rest on explicit or tacit principles and norms that seek to lead participants into new patterns of international behavior, specific rules about what is permissible behavior and procedures that guide mutual policy choices. Simpson and Howlett (1994) argue that the nuclear nonproliferation regime is an international security regime which can make a serious impact on the interests of party states.[183]

Kessler (1995) describes four elements that constitute the ideal form of an international control regime, and applies his concept to the nuclear nonproliferation regime.[184] He introduces the concept of

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[179] M. Bell and K. Pavitt, "Technological Accumulation and Industrial Growth: Contrasts between Developed and Developing Countries," *Industrial and Corporate Change* 2, no. 2 (1993).
[180] Marcelle, *Policy Briefs, Technology Acquisition and Domestic Learning.*
[181] M. Magdalena and Martin Martinez, *National Sovereignty and International Organization* (Leiden, The Netherlands: Martinus Nijhoff Publishers, 1996)., p.294.
[182] Michael Brzoska, "Is the Nuclear Non-Proliferation System a Regime? A Comment on Trevor Mcmorris Tate," *Journal of Peace Research* 29, no. 2 (May 1992).
[183] Simpson and Howlett also provided very good definition on the nuclear non-proliferation regime. "The nuclear non-proliferation regime is an integrated network of treaties and others standard-setting arrangements which provide a comprehensive framework for the behavior of states, and international organizations and other actors, in the nuclear area. John Simpson and Daryll Howlett, "The NPT Renewal Conference: Stumbling toward 1995," *International Security* 5, no. 1 (Summer 1994).
[184] Kessler, *Verifying Nonproliferation Treaties: Obligation, Process, and Sovereignty.*, p.9.

“control regime” to make non-proliferation regimes for nuclear weapons, biological-chemical weapons, and weapons of mass destruction (WMD) the main purpose of his analysis.

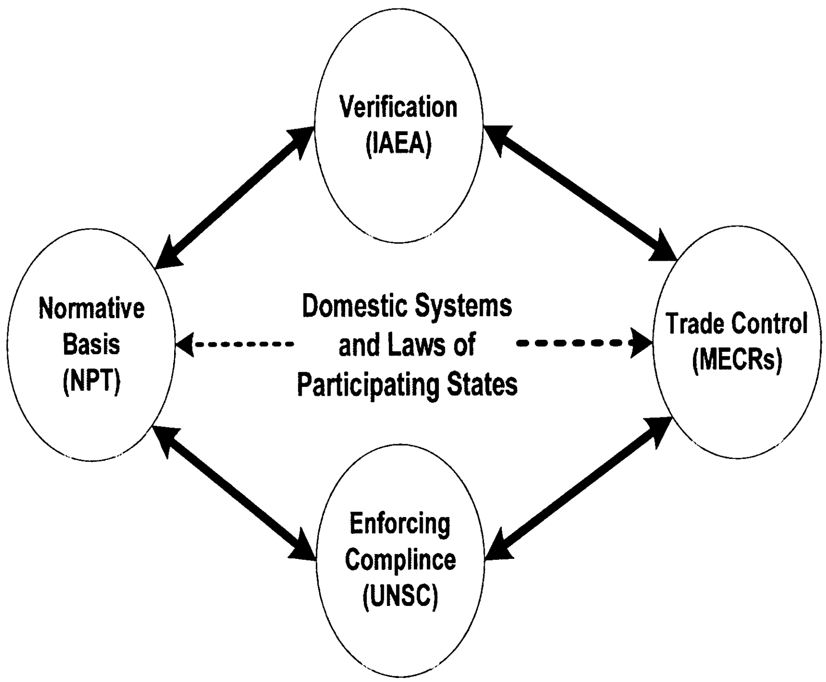

Figure 5.4 Overall Structure of NPT Regime based on Kessler's Definition

This paper will use the definition proposed by the CRS report as follows:

> *“The nuclear nonproliferation regime encompasses several treaties, extensive multilateral and bilateral diplomatic agreements, multilateral organizations and domestic agencies, and the domestic laws of participating countries.”* [185]

This CRS' definition is strongly supported by Brzoska's (1992) definition of international regimes in the sense that his definition allows for the consideration of all kinds of arrangements within an issue area, not bound to specific institutions. All of the NPT regime components mentioned above vary greatly in terms of what needs to be controlled, the degree of legal authority, and the number and characteristics of member states. Table 5.2 shows the summary of current NPT regime components that work toward nonproliferation of nuclear weapons.

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[185] Sharon A. Squassoni, Steven R. Bowman, and Carl E. Behrens, "CRS Report for Congress: Proliferation Control Regimes: Background and Status," (Washington DC: 2006)., p.10.

Table 5.2 Summary of NPT Regime Components

Classification		Background / Legal authority	Year
Treaty	NPT	International Treaty [186]	1970
International Organizations	International Atomic Energy Agency	Statute of the IAEA (1956)	1957
	UN Conference on Disarmament	The first Special Session on Disarmament of the United Nations General Assembly (1978)	1978
	UN Disarmament Committee	Disarmament Committee of 1952	1978
	UN Security Council	UN Charter Chapter V and VII	1946
Multilateral Export Control Regimes	Zangger Committee	Article III.2 of the NPT	1970
	Nuclear Suppliers Group	Ford Administration Initiative	1974
	IAEA	INFCIRC/254 [a]	1978
	Wassenaar Arrangement	Former COCOM export control regime	1996
Complementary Treaties	Partial Test Ban Treaty	Agreement in the form of Treaty	1963
	Comprehensive Test Ban Treaty	UNGA resolution 48/70 (1993)	1996
	Fissile Material Cutoff Treaty	UNGA Resolution 48/75L (1993)	1995
	Nuclear Weapons Free Zone	UN, Article VII of the NPT	1970
Multilateral Efforts [a]	Proliferation Security Initiative	UNSC 1540 committee The National Strategy to Combat Weapons of Mass Destruction (2002)	2003
	Non-military	Diplomatic and economic measures based on agreements	-
Domestic Systems and Regulations		National legislation and administrative authorities	-

Note: [a] Communication Received from Certain Member States Regarding Guidelines for the Export of Nuclear Material, Equipment or Technology

[186] A Treaty is an agreement in written form between nation-states (or international agencies, such as the United Nations, that have been given treaty-making capacity by the states that created them) that is intended to establish a relationship governed by international law. Various terms have been used for such an agreement, including treaty, convention, protocol, declaration, charter, covenant, pact, act, statute, exchange of notes, agreement, modus Vivendi, and understanding. The UN Charter states that treaties must be registered with the UN to be invoked before it or enforced in its judiciary organ, the International Court of Justice.

5.7 The Treaty of the Non-Proliferation of Nuclear Weapons (NPT)

The NPT is the key treaty that sets up standards for the international nonproliferation regime, and the NPT provides the legal and institutional basis for this regime. The treaty is often interpreted as having three pillars: non-proliferation, disarmament, and the right to peacefully use nuclear technology. The text of the NPT was negotiated between 1961 and 1968 and the Treaty was opened for signature on July 1, 1968.

Table 5.3 Problematic Articles in the NPT

Classification	Article	Statements related	Cases
Ambiguous legal Interpretation	Art II	"..not seek or receive any assistance in ***the manufacture of nuclear weapons***...."	-
	Art III	"...agreements shall commence ***within 180 days*** from the original entry into force..." "...agreements shall enter into force not later than ***eighteen months***..."	North Korea
	Art IV	"Nothing....shall be interpreted as affecting ***the inalienable right*** ....to develop research, production and use of nuclear energy....[187]	Iran
	Art V	"...potential benefits from ***peaceful applications of nuclear explosions***..."	India
Ambiguous legal Interpretation	Art X	"Each party.....***have the right to withdraw*** from the Treaty" [188] "...give ***the notice*** of such withdrawal ...to the ***United Nations Security Council three months in advance***...."	North Korea[189]
Inherent defect	Art I, VI	Nuclear Disarmament	
	Art VII	"...the right of any group of states to conclude regional treaties for the total absence of nuclear weapons."	NWFZ
Absent provision	N/A	Enforcement and punishment	North Korea Iran
		Security assurance	UNSC resolutions [a]

Note: [a] UNSC Resolutions 255 (1968) and 984 (1995)

[187] Xinjun Zhang, "The Riddle of Inalienable Right in Article IV of the Treaty on the Non-Proliferation of the Nuclear Weapons: Intentional Ambiguity," *Chinese Journal of International Law* 5, no. 3 (2006).; Robert Zarate, "The NPT, IAEA Safeguards and Peaceful Nuclear Energy: An "Inalienable Right," but Precisely to What?," (Washington D.C.: Nonproliferation Policy Education Center, 2007).

[188] George Bunn and John Reinelander, "The Right to Withdraw from the NPT: Article X Is Not Unconditional," *Disarmament Diplomacy* 79 (April/May 2005).; Jenny Nielsen and John Simpson, *The NPT Withdrawal Clause and Its Negotiating History* (Mountain Center for International Studies (MCIS), July 2004 [cited Jan. 10 2009]).

[189] Frederic L. Kirgis, *North Korea's Withdrawal from the Nuclear Nonproliferation Treaty," , (Jan. 2003)* (The American Society of International Law (ASIL), Jan. 2003 [cited Apr. 4 2008]); available from http://www.asil.org/insigh96.cfm#author.

The NPT entered into force on March 5, 1970. As of today, there are 189 signatories to the treaty. The treaty established five Nuclear Weapons States (NWS), including the U.S., Britain, China, France, and Russia. As a result, the NPT has discriminatory features in its nature by allowing the NWS to possess nuclear weapons, while prohibiting the Non-NWS (NNWS) from developing nuclear weapons. Consequently, nonproliferation of nuclear weapons (***horizontal proliferation***) is stressed but disarmament of nuclear weapons (***vertical proliferation***) is often disregarded. More importantly, the NPT set up an inspection system it calls "safeguards," based on agreements between NNWS and the IAEA.

A legal review of the articles of the NPT is critical before discussing the potential of the NPT regime. Although the treaty has been successful for nearly 40 years, it has faced difficulty because of the drawbacks in its nature, as shown in Table 5.3. The legal problems of the NPT context can be divided into ambiguity, unreality or idealism, and lack of enforcement clauses. Articles II, III, IV, V, and X are ambiguous, Article I, VI, VII are far from implementation without the strong political will of the five NWSs. Most importantly, the NPT lacks an enforcement clause as well as provision of a security guarantee.[190]

There is no explicit organization for the NPT; instead, the NPT Review Conference is held at UN headquarters every five years with the objective of reviewing the operation of the Treaty in accordance with Article VIII. Before the NPT review conference, the Preparatory Committee (PrepCom) is generally set up, and holds three sessions to address substantive and procedural issues during the upcoming Review Conference.

5.8 International Organizations

5.8.1 United Nations (UN)

The global efforts for achieving nonproliferation and arms reduction are being made under the leadership of the UN. The UN is an international organization whose main functions include maintenance of international peace and security, arms control and disarmament, economic welfare and cooperation, social welfare and cooperation, dependent areas, and development of international law. Figure 5.5 shows the five administrative bodies in the UN and the linkage between the UN and the NPT regime.

[190] From the outset of the negotiations on the NPT in the 1960s, many non-nuclear-weapon states made clear that in exchange for commitments not to acquire nuclear weapons they expected certain assurances from nuclear-weapon states. It was not possible to include such a provision in the NPT. John Carlson, "Views on Regional Non-Proliferation Arrangements" (paper presented at the INMM/ESARDA Workshop, Tokyo, Japan, November 13-16 2000).

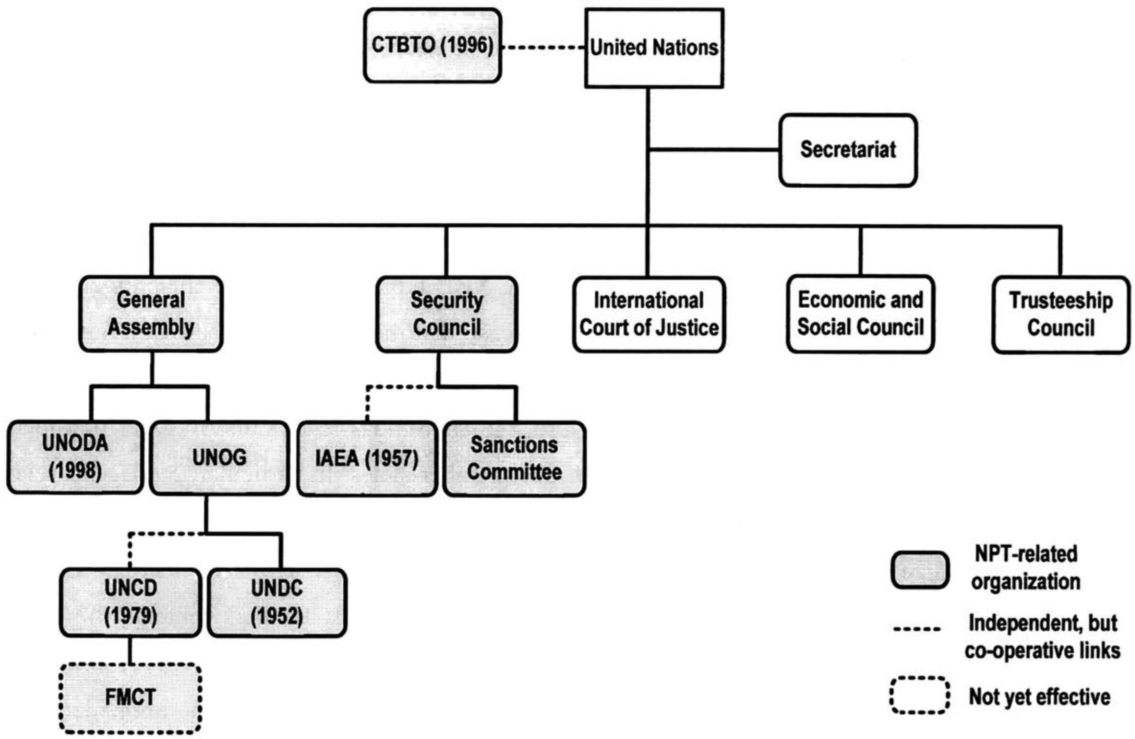

Figure 5.5 United Nations Organs related to Nonproliferation of Nuclear Weapons[191]

A. United Nations Security Council (UNSC)

Among five administrative bodies of the UN, the UNSC is the strongest organ in terms of legal authority from the perspective of international law. Important subsidiary bodies of the UNSC are the **Military Staff Committee** (MSC) and **sanctions committees**. Chapter VII of the UN Charter (Actions with Respect to Threats to the Peace, Breaches of the Peace, and Acts of Aggression), which came into force on 24 October 1945, gives the United Nations Security Council (UNSC) the power to adopt enforcement actions in the event of any threat to the peace, breach of the peace or act of aggression. Though there is some disagreement over the legal power of the UNSC, the International Court of Justice (ICJ) declared that the UNSC has the sole power to require enforcement by coercive action in 1962.

Legal powers of the UNSC are exercised by adopting resolutions. Types of UN resolutions can be classified into recommendations and decisions, with the latter type legally binding. Pursuant to Chapter VII, the UNSC may decide to adopt resolutions that create obligations on its addressees.[192] Article 41 and Article 42 stipulate the use of non-military and military measures, respectively "to

[191] UNOG (United Nations Office at Geneva), UNODA (United Nations Office for Disarmament Affairs), UNCD (United NationsConference on Disarmament), UNDC (United Nations Disarmament Commission), and CTBTO (Comprehensive Test Ban Treaty Organization).

[192] Marko Divac Öberg, "The Legal Effects of Resolutions of the Un Security Council and General Assembly in the Jurisprudence of the ICJ " *The European Journal of International Law* 16, no. 5 (2006).

maintain or restore international peace and security." In general, non-military measures, including economic sanctions and diplomatic sanctions in the form of sanctions, have been preferred and applied by the UNSC.

The role of the UNSC in relation to the NPT regime has been increasing. First, it relates to Article X of the NPT with regard to the states' right to withdraw from the NPT. Even though the role of UNSC in this matter is not clearly stated, the UNSC is the only organ that can stop arbitrary withdrawal of proliferators. Second, the UNSC can complement the NPT in the sense that it is the only element that has enforcement resources in the NPT regime. In the case that the IAEA refers the violation of IAEA safeguards to the UNSC, the UNSC can issue resolutions to take actions against proliferators, including economic, diplomatic, and military sanctions. Third, the UNSC has legal authority over non-member states to the NPT because all non-NPT stares are UN member states. In particular, the UNSC released its resolution 1540 in 2004, which calls for swift passage of the ***UNSC Resolution 1540*** requiring all states to criminalize proliferation, enact strict export controls, and secure sensitive materials within their borders. The 1540 committee collated legislative data of member states that contains the status of national implementation of UNSC 1540.[193] Some states outside the NPT such as Israel and Pakistan followed the UNSC resolution 1540, but North Korea did not report its status of the implementation of requirements.

B. United Nations General Assembly (UNGA)

UN General Assembly (UNGA) was established in 1945 under the UN Charter. The UNGA comprises all 192 Members of the UN and it is the chief deliberative organ of the UN, providing a unique forum for multilateral discussion of the full spectrum of international issues covered by the Charter. Pursuant to its "Uniting for Peace" resolution of November 1950 (resolution 377 (V)),[194] the Assembly may also take action if the Security Council fails to act, owing to the negative vote of a permanent member, in a case where there appears to be a threat to the peace, breach of the peace or act of aggression.[195] The Assembly can consider the matter immediately with a view to making recommendations to members for collective measures to maintain or restore international peace and security through special sessions and emergency special sessions. In relation to the NPT regime, in 1993, UNGA released **consensus resolution (48/75L)** that convinces a non-discriminatory, multilateral and internationally and effectively verifiable treaty banning the production of fissile material for nuclear weapons or other

[193] This database has been developed by the Committee established pursuant to UNSC Resolution 1540 (2004) for the purpose of providing additional information on the national implementation of regulations and measures related to the resolution.

[194] For more information, see UN Dag Hammarskjöld Library, ([cited Aug. 8 2008]).<http://www.un.org/Depts/dhl/landmark/pdf/ares377e.pdf>

[195] In general, the UN General Assembly (UNGA)'s resolutions are known for having only a recommendatory effect as a declarative statement; thus, UNGA's resolutions lack the legal authority except for the case that the states agree to accept the UNGA's resolutions as binding. Mohamed Sameh M. Amr, *The Role of the International Court of Justice as the Principal Judicial Organ of the United Nations* (Hague, The Netherlands: Kluwer Law International, 2003).pp.171-173.

nuclear explosive devices, i.e., the Fissile Material Cutoff Treaty (FMCT), would be a significant contribution to nuclear non-proliferation in all its aspects.

C. United Nations Conference on Disarmament (UNCD)

The UNCD is the successor to various Geneva-based arms control bodies dating back to 1960. The Conference on Disarmament was established in 1979 as the single multilateral disarmament negotiating forum of the international community, and this was a result of the first Special Session on Disarmament of the United Nations General Assembly held in 1978. The terms of reference of the UNCD include practically all multilateral arms-control and disarmament problems. The CD is regarded as ***an autonomous body***, although it has a close relationship with the United Nations. The focus of the UNCD are: cessation of the nuclear arms race; nuclear disarmament; prevention of nuclear war; prevention of an arms race in outer space; effective international arrangements to assure non-nuclear-weapon states against the use or threat of use of nuclear weapons, new types of weapons of mass destruction and new systems of such weapons, including radiological weapons; and a comprehensive program of disarmament and transparency in armaments. The CD holds three sessions each year. During the second session of 1995 in March, the Conference on Disarmament (CD) agreed by consensus to establish an *Ad hoc* Committee with a mandate to negotiate a cutoff treaty based on the 1993 UN General Assembly's ***consensus resolution (48/75L)***. The CD adopted a mandate to negotiate a ban on the production of fissile materials for nuclear weapons - The Fissile Materials Cut-off Treaty (FMCT); however, negotiations have not started, as CD members have struggled to adopt a work program. The CD can only approve decisions by consensus, and the insistence of a few states to link FMCT negotiations to other nuclear disarmament issues has not produced tangible outcomes.

D. United Nations Disarmament Commission (UNDC)

The United Nations Disarmament Commission (UNDC) is a deliberative body and a subsidiary organ of the UNGA, which is mandated to consider and make recommendations on various disarmament related issues and to follow up the relevant decisions and recommendations of the special sessions devoted to disarmament held thus far. The UNDC was originally established in 1952 and ceased to convene after 1965. It was re-established and strengthened at the first Special Session of the General Assembly devoted to Disarmament in 1978 to succeed an earlier Disarmament Commission.

The UNDC reports annually to the General Assembly and has dealt with numerous disarmament-related problems, including both nuclear and conventional. The UNDC has submitted guidelines and principles on various subject items, including guidelines for appropriate types of confidence-building measures, guidelines and recommendations for regional approaches to disarmament within the context of global security, and guidelines and recommendations for objective information on military matters.

5.8.2 International Atomic Energy Agency (IAEA)

The IAEA was set up as the world´s "Atoms for Peace" organization in 1957 within the United Nations family. When the NPT entered into force in 1970, the **IAEA** was entrusted with key roles and responsibilities**.** Since then, the **IAEA** has been the "international safeguards inspectorate and a multilateral channel for transferring peaceful applications of nuclear technology." The IAEA Statute guides the IAEA's mission and the vision. The Agency works with its Member States and multiple partners worldwide to promote safe, secure and peaceful nuclear technologies. The IAEA´s mission is referred to as three main pillars: Safety and Security; Science and Technology; and Safeguards and Verification. Its key roles are making a contribution to international peace and security, and to achieve social, economic and environmental development.

5.9 Multilateral Export Control Regimes (MECRs)

There are currently five export control regimes: the Zangger Committee (ZC or ZAC), Nuclear Suppliers Group (NSG), Australia Group (AG), Missile Technology Control Regime (MTCR), and Wassenaar Arrangement (WA). All of these regimes have linkage with the NPT regime in varying degrees. Multilateral Export Control Regime (MECR) is a common term describing these systems, which regulate the supply of major conventional arms systems and materials in association with weapons of mass destruction (WMD). MECRs prevent transfers that contribute to the spread of weapons of mass destruction.

MECRs can help deter proliferation by: raising the cost of proliferation; providing signals that countries are attempting to acquire WMD; and slowing efforts to acquire WMD. ZC, NSG, and WA are worth mentioning with regard to the NPT regime. Especially, ZC and NSG are dedicated to the NPT regime. Participating countries of these export control regimes would inform this organization of all sensitive nuclear or nuclear-related exports, and have the mandate and legal rights to verify that the transactions are indeed legal.

Table 5.4 Multilateral Export Control Regimes (MECRs)

Regime	Control Items and Lists	Legal Basis
ZC (1974)	The Trigger List for controlling nuclear sensitive materials and equipment	NPT III.2 (INFCIRC/209)
NSG (1977)	Two control lists; Part I and Part II •Part 1 : Guidelines for Nuclear Transfers •Part 2: Guidelines for Transfers of Nuclear-Related Dual-Use Equipment, Material and Related technology.	NPT III.2 (INFCIRC/254)
AG (1985)[196]	Control lists	CWC and BTWC
MTCR (1987)	MTCR Guidelines and the Equipment, Software, and Technology Annex Category 1 items and Category 2 items	No supporting treaty
WA (1996)	•List of Dual-Use Goods and Technologies; Tier 1-Basic, Tier 2-Sensitive •List of munitions (7 categories)	None (The weakest[197])

Note: CWC and BTWC stand for Chemical Weapons Conventions and the Biological and Toxin Weapons Convention, respectively.

The ZC, the NSG and the AG are considered to be more effective than the MTCR and the WA due to the existence of supporting treaties.[198] ZC and NSG had been enhanced after the crisis with the Iraq's nuclear weapons program. [See Appendix C for current status]

5.9.1 Zangger Committee (ZC)

The Zangger Committee, also known as the ***Nuclear Exporters Committee (NEC)***, was established in 1974. The purpose of the ZC is to provide clear interpretation of Article III.2 (material and equipment control) of the NPT that provides legal background for the ZC. Nuclear export control policies of the ZC for NPT Parties and specific details are documented in INFCIRC/209 of 1974. The ZC has its own trigger list for controlling nuclear sensitive materials and equipment and these are incorporated as Annex II in the Additional Protocol. Only NPT signatories can be a member of ZC, which is distinct from the NSG. The **ZC** maintains and updates a Trigger List (triggering safeguards as a condition of supply) of nuclear-related strategic goods to assist NPT Parties in identifying equipment and materials subject to export controls. The ZC reports a trigger list to the Secretary General of the IAEA.

[196] Australia Group participants are now playing an active and constructive role in the Organization for the Prohibition of Chemical Weapons (OPCW) in The Hague.
[197] However, WA is the only regime that has existing infrastructure and permanent Secretariat in Vienna among MECRs. In addition, WA was set to strengthen international security by promoting transparency and responsible exports of conventional arms and dual-use goods. Its overall purpose was to prevent "destabilizing accumulations" of conventional weaponry.
[198] Michael Beck, "Viewpoint: Reforming the Multilateral Export Control Regimes," *The Nonproliferation Review* (Summer 2000).

5.9.2 Nuclear Suppliers Group

The ***Nuclear Suppliers Group (NSG)*** was established as a Ford Administration initiative in 1975. Often called "London Club,"[199] the NSG had meetings in London between 1975 and 1977 to agree on steps to reduce the risk of commercial competition undermining safeguards commitments, especially the transfer of sensitive uranium enrichment and plutonium reprocessing technologies and the requirement of full-scope safeguards prior to nuclear purchases.[200] The NSG guidelines were first published in February 1978 as IAEA document INFCIRC/254. Establishing the guidelines, the NSG members did not openly institutionalize the cooperation.[201] Since then, the NSG did not go on meeting after adopting the guidelines while the NSG had influenced the export policies of the members on a bilateral basis until 1980s. Iraqi nuclear weapons program discovered in the early 1990s made multilateral cooperation within the NSG important again.[202]

What makes the NSG different from the ZC are as follows: first, the Non-NPT signatory can be a member.[203] Second, different from ***trigger list items*** of the Zangger Committee that lists EDPs, Dual-Use Items (DUIs) of the NSG do not generally qualify for regular reporting to the IAEA because of their lower level of significance and limited scope of controllability as well as the limited information management capacity of the IAEA.[204]

5.9.3 Wassenaar Arrangement (WA)

The Wassenaar Arrangement (WA) was designed to foster multilateral cooperation to promote transparency, exchange of views and information and greater responsibility in transfer of conventional arms and dual-use goods and technologies. The WA is the successor of the Coordinating Committee for Multilateral Strategic Export Controls (COCOM) during the Cold War era, which was formally dismantled in 1994. The WA countries maintain effective export controls for items on agreed lists based on common understandings of risks associated with the transfer of these items. The List is incorporated by WA Participating States in their national legislation. The WA Secretariat provides support to the

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199 Tate, "Regime-Building in the Non-Proliferation System."

200 The Nuclear Suppliers Group imposed curbs on selling nuclear fuels and equipment to India from 1974 to 2008. Indiasaver.com, *France to Sell Nuclear Reactors and Fuel to India* (Indiaserver.com, 2008 [cited Jan. 11 2009]); available from <http://www.india-server.com/news/france-to-sell-nuclear-reactors-and-4123.html>.

201 Ham, "An Integrated Methodology for Quantitative Assessment of Proliferation Resistance of Advanced Nuclear Systems Using Probabilistic Methods"., p.16. The principal reason for this was due to the opposition among developing countries that regarded the NSG as a supplier cartel preventing the applications of nuclear energy for peaceful purposes.

202 Ian Anthony et al., *Reforming Nuclear Export Controls: The Future of the Nuclear Suppliers Group, SIPRI Research Report No.22* (Oxford, U.K.: Oxford University Press, 2007).

203 All ZC members participate in the NSG. But Belarus, Brazil, Cyprus, Estonia, Kazakhstan, Latvia, Lithuania, Malta and New Zealand participate only in the NSG as of Sep.2006.

204 NSG members currently share only the information about the denials. NSG, in combination with the IAEA, should share both any denials of an export and key approvals. Fritz W. Schmidt, "Nuclear Export Controls Closing the Gaps," *IAEA Bulletin* 46, no. 2 (Mar. 2005).

plenary meetings and sub-groups, and facilitates the Participating States for their information exchange process with the help of the Wassenaar Arrangement Information System (WAIS).[205]

5.9.4 Challenges

The problems of the MECRs arose as the A. Q. Khan network that sold nuclear program elements to North Korea, Iran, and Libya was revealed in the early 2000s. The A. Q. Khan network was masterful in making use of loopholes in the MECRs. The network identified countries that had inadequate national export laws yet adequate industrial capability for the network's purposes; these countries were both inside and outside the Nuclear Suppliers Group. The network also knew how to obtain equipment from countries in Europe with stringent export control systems. As can be concluded from this fact, having a unified and effective system of dual-use export controls is now more important than ever before. [206]

The problems of current MECRs can be summarized as follows: First, MECRs are not a legally binding regime because they rely upon informal arrangements[207] and thus MECRs have no choice but to depend on the basic principle of cooperation with restrictions as the exception. Consequently, MECRs are limited in membership and verifying noncompliance of participating states. Second, the complexity of each regime's trigger list hinders participating state from sharing information among them or with the IAEA. Third, participating states inherently have very low level of will to comply with MECRs. The authorities are unlikely to carefully scrutinize exports or encourage curiosity about the actual end-use of an item because it is very hard to know the actual purpose of the materials or the parts they were contracted to make. In addition, the companies had little motivation to confirm the explanations about the end-use of the items. Four, cooperation between MECRs and the IAEA has not been clearly established yet. Export control information is not systematically shared with the IAEA primarily due to the enormous volume of information as well as ineffective cooperation between the IAEA and MECRs.[208] [See Appendix C]

Figure 5.6 shows how development and dispersion of nuclear technology impacted the efficiency of nuclear trade control. This figure also includes how expansion of membership to MECRs would work for the efficiency of MECRs.

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[205] Sune Danielsson, "Basic Information on the Wassenaar Arrangement," in *Wassenaar Arrangement Export Control and Its Role in Strengthening International Security*, ed. Auer Dorothea (Vienna, Austria: Vienna School of International Studies, Jan. 2005).
[206] David Albright and Corey Hinderstein, "Uncovering the Nuclear Black Market: World toward Closing Gaps in the International Nonproliferation Regime" (paper presented at the 45th Annual Meeting for the INMM, Orlando, FL July 2 2004).).
[207] Charles Lipson, "Why Are Some International Agreements Informal?," *International Organization* 45, no. 4 (Autumn 1991).
[208] Schmidt, "Nuclear Export Controls Closing the Gaps."

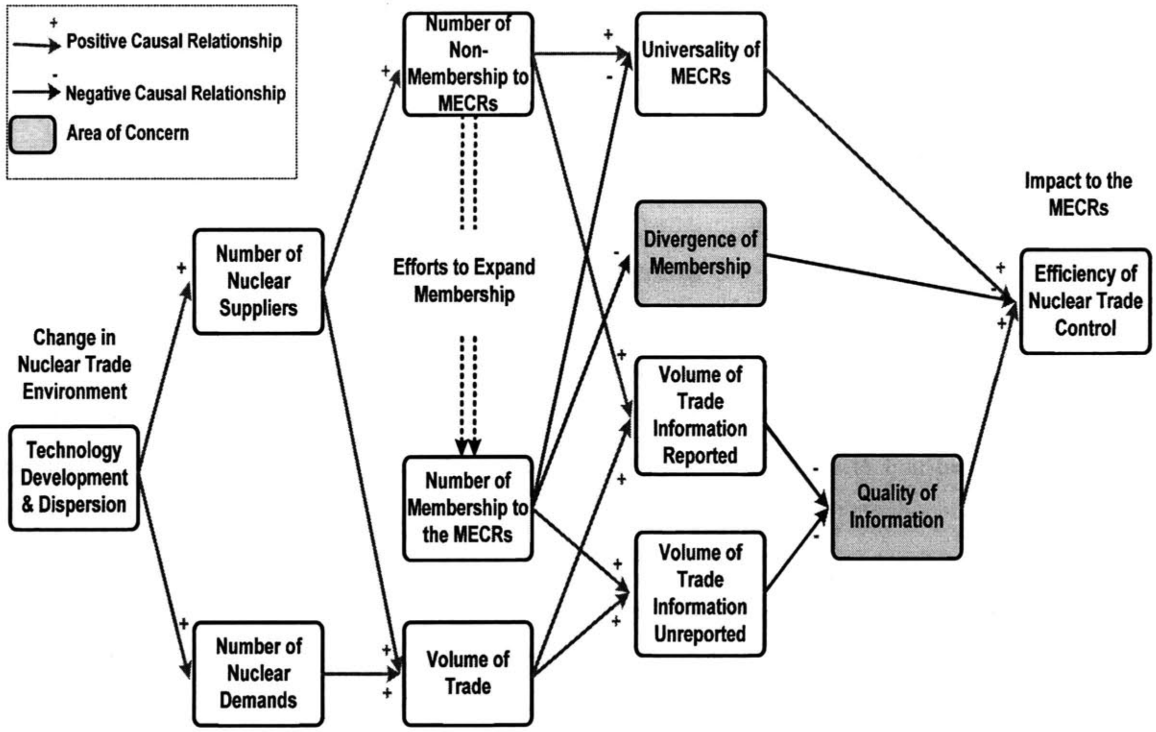

Figure 5.6 Causal Links in the MECRs

5.10 Complementary Treaties

5.10.1 Nuclear Weapon Free Zone (NWFZ)

The concept of a nuclear weapon free zone (NWFZ) was first developed in the late 1950s, as a possible complementary measure to the efforts of the international community towards establishing a global non-proliferation regime. [209] A NWFZ is defined by the UN as an agreement, generally by internationally recognized treaty, to ban the use, development, or deployment of nuclear weapons in a given area. A specified region in which countries commit themselves not to manufacture, acquire, test, or process nuclear weapons. A NWFZ can provide mechanisms of verification and control to enforce its obligations. Hence, a NWFZ is conceived as incremental measures toward total nuclear disarmament, and these agreements have steadily grown in number since the first, governing Antarctica.

The Article VII of the NPT affirms the right of countries to establish specified zones free of nuclear weapons. The UN General Assembly reaffirmed that right in 1975 (UNGA Resolution 3472). Band outlined the criteria for such zones. Among basic elements of NWFZ are a treaty that establishes

[209] The Soviet Union first introduced the idea of a NWFZ in Central Europe at the United Nations General Assembly in 1956. James Martin Center for Nonproliferation Studies (CNS), *NWFZ Clearinghouse* (May 13 2008 [cited Jun. 14 2008]); available from <http://cns.miis.edu/nwfz_clearinghouse>.

regions for no nuclear weapons and a protocol for ratification; provision of negative security by NWSs; and acceptance of comprehensive verification measures administered by the IAEA. [210]

Table 5.5 Examples of NWFZs

Name	Region	Opened for signature	Entered into force
Treaty of Tlatelolco	Latin America and the Caribbean	1967	2002
Treaty of Bangkok	ASEAN states	1995	1997
Treaty of Rarotonga	The South Pacific	1985	1986
Central Asian Nuclear Weapon Free Zone	Kazakhstan, Krygyzstan, Tajikistan, Turkmenistan, and Uzbekistan	2006	Not yet
Treaty of Pelindaba	African Nuclear Weapons Free Zone Treaty	1996	Not yet

The contribution made by NWFZs to nonproliferation of nuclear weapons has been widely acknowledged. In practice, it is hard to establish NWFZs where suitable areas cannot be defined easily and the level of trust among states in the region is relatively low. No NWFZ has been established in a region that includes the territory of any of the five NWSs that are party to the Treaty on the Non-Proliferation of Nuclear Weapons as well as three states - Israel, India and Pakistan - that are not. The Middle East is a good example. It seems unlikely that the Middle East will establish NWFZs in the foreseeable future. In addition, it was reported that no African Arab state will ratify the Treaty of Pelindaba until Israel, which is just outside the zone, renounces its nuclear weapons program. Though they are not NWFZ-type treaties, three treaties for Banning Nuclear Weapon Deployment are worth mention: the Antarctic Treaty; outlaw of Nuclear Weapons by Austria with the Atomsperrgesetz in 1999; and declaration of denuclearization on the Korean Peninsula.

5.10.2 Fissile Material Cutoff Treaty (FMCT)

The UN proposed the negotiation of a fissile materials production banning treaty (hereinafter, FMCT) in December 1993 through UNGA consensus resolution (48/75L), after US President Clinton called for a multilateral convention banning the production of fissile materials for nuclear explosives or outside international safeguards. The UNCD was assigned the venue for negotiating a FMCT since 1995. The

[210] Carlson, "Views on Regional Non-Proliferation Arrangements".

widespread international support for an FMCT was obtained through the NPT RC at the 1995 and 2000 NPT Review Conference.[211]

Ideally, the most important feature of the FMCT should be non-discriminatory standards toward both NWS and NNWS with universal and Comprehensive Safeguards Agreements (CSA) unlike the NPT.[212] The treaty would expand the membership, including five NWSs and States Outside the NPT (SON), into a verification regime. A verification regime for the FMCT will be similar to comprehensive safeguards in the NNWS but the application will be expanded to NWSs and SONs. The FMCT may require all production facilities of direct-use material to be either shut down or converted to civilian use and subject to safeguards.

Issues

To date, the UNCD has not been able to start such negotiation as it has not been able to reach agreement on its substantive program of work. The start of negotiations on an FMCT is not likely to occur in the near future because of three fundamental issues that are preventing states from starting negotiation for the FMCT as shown in Figure 5.7.

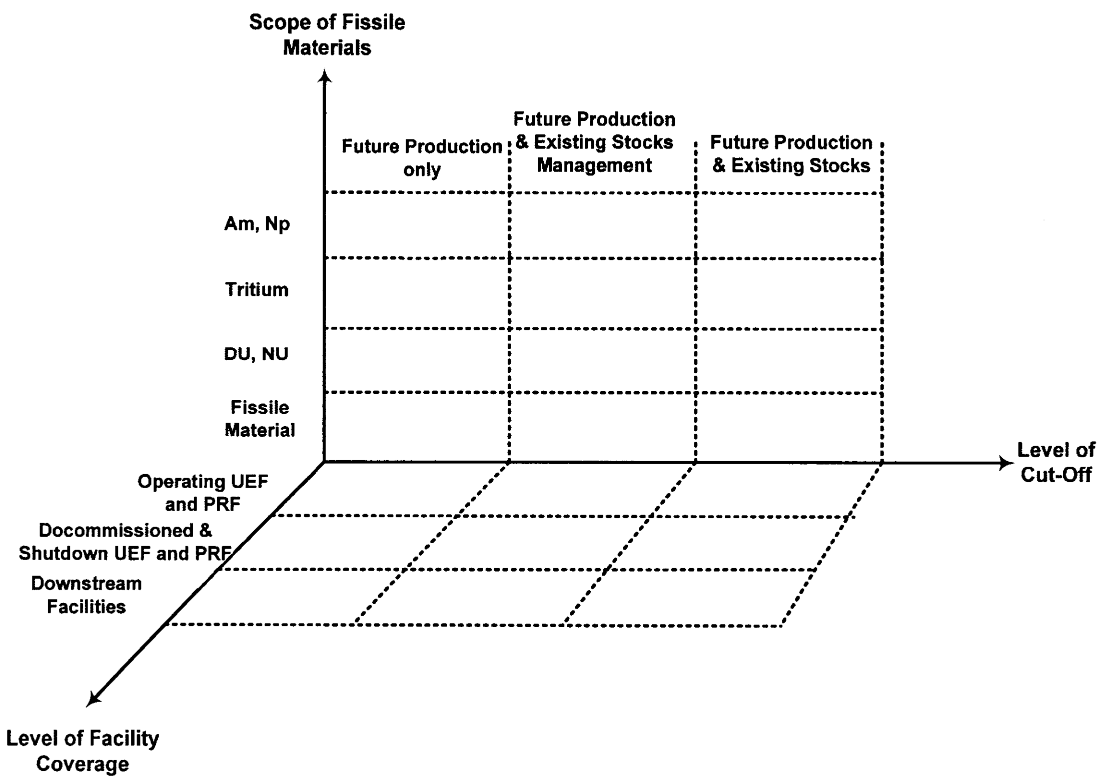

Figure 5.7 Varying Degrees of Scopes for FMCT

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211 Defense Treaty Inspection Readiness Program (DTIRP) <http://dtirp.dtra.mil/TIC/synopses/fmct.cfm> and Reaching Critical Will <http://www.reachingcriticalwill.org/legal/fmct.html>.

212 Annette Shaper, "Verification of a Fissile Material Cut-Off Treaty," *Disarmament Forum*, no. Two (1999).

The First issue is about the level of fissile material cut-off. The issue of existing stocks blocked consensus on the negotiation of an FMCT. If existing stocks are included in a FMCT, it would be a great burden for the NWS because downblending of existing stocks of weapons-grade fissile materials is required. If not included, materials produced in the future may be falsely declared as earlier production or existing stocks may be flown to NNWS or non-state actors. The Second issue is related to the scope of the fissile materials, namely, what kinds of materials need to fall into the category of control. Tritium, depleted uranium and natural uranium are used for manufacturing advanced nuclear weapons. Furthermore, it is reported that Americium and Neptunium can be used for nuclear weapons. Military HEUs for naval fuels can pose another challenge against a FMCT from different perspective. The Third issue concerns the level of verification coverage for different facilities. The most feasible scenario is to place currently-operating reprocessing plants and uranium enrichment plants under safeguards for verification.[213]

5.10.3 Test Ban Treaty – PTBT (LTBT) and CTBT (1996)

A. Partial Test Ban Treaty (PTBT)

Since the test of the first nuclear bomb, Trinity, on July 16, 1945, more than 2,000 nuclear tests were conducted worldwide until 1998. The peak of nuclear weapons tests occurred in 1962. Atmospheric tests by the two superpowers generated about 72 MT of nuclear explosive yield as fallout in a single year. The next year, the US, USSR, and the UK - but neither China nor France - signed the Partial Test Ban Treaty (PTBT) or Limited Test Ban Treaty (LTBT) in Moscow on 5 August 1963. The Treaty prohibited nuclear explosions within the Earth's atmosphere, oceans, and outer space, while not banning tests underground.[214] These nuclear tests have generated concern with regard to negative environmental consequences. When a nuclear test is executed, it promptly generates a huge amount of thermal energy and massive doses of neutron, x-rays and gamma-ray radiation. These types of radiation cause dangerous radiation exposure to the ecosystem of the earth. [215]

B. Comprehensive Test Ban Treaty (CTBT)

United Nations General Assembly (UNGA) passed ***resolution 48/70*** by consensus supporting the multilateral negotiation of a CTBT in 1993. This is the first time that a consensus resolution in support of a CTBT has been adopted by the UNGA. The Treaty was opened for signature on 24 September 1996. The UN Secretary-General is the depositary of the Treaty, and convenes, upon the request of a majority of ratifying states, the conferences on facilitating the entry into force of the Treaty.

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[213] Hui Zhang, *FMCT Verification: Case Studies, IAEA-SM-367/9/04* (IAEA, 2004).
[214] Since the LTBT was signed in 1963 by the U.S, U.K. and Soviet Union, nuclear detonations by these countries have been underground. France and China were not parties to the LTBT, their tests gradually moved from the open atmosphere to subterranean sites-underground and under the sea.
[215] Moody, Hutcheon, and Grant, *Nuclear Forensics Analysis*.

The Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), as an interim and independent organization, was established on 19 November 1996. This Commission would lay the groundwork required and build up the global verification regime to monitor compliance with the Treaty.[216] The CTBTO has its own membership and budget, but it has a relationship agreement with the United Nations since 2000. The Agreement provides a framework for cooperation between the two organizations.

The CTBT adds no new obligation to non-nuclear weapons states that are parties to the NPT. The Treaty is neither intended to force NWS to give up their nuclear weapons nor to reduce the number of nuclear weapons. The CTBT would simply create a new international norm against the testing of nuclear weapons. Nonetheless, it has not yet entered into force,[217] and some of the states of greatest concern are unlikely to sign it in the foreseeable future. Even the U.S. Senate declined to ratify the CTBT submitted by President Clinton on October 13, 1999.

5.11 Ad-hoc Multilateral Efforts: Non-Military and Military

5.11.1. Non-Military Multilateral Efforts

Non-military measures are used when one wants to change a state's behavior without resorting to military options. The purpose of non-military efforts is to create a situation where a proliferator concludes that the costs of a nuclear weapons programs exceed the benefits. Non-military efforts were successful during the Cold-War Era, but effects have been weakened over time. Multilateral non-military efforts can be divided into intelligence cooperation, diplomatic efforts, and economic efforts.

A. Intelligence Cooperation

Cooperation among the intelligence community can significantly enforce the strengths of the regime in the early detection of nuclear weapons programs by sharing a variety of information with regard to nuclear proliferation activities. The early detection would provide the broad opportunity and flexibility for the engagement of the international community in the form of diplomatic, military, economic intervention. For example, the U.S. intelligence community's secret penetration of the Khan network led to the seizure of the ship BBC China bound for Libya.[218] The success of nuclear weapons program

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[216] Legal aspects of the CTBT are well-explained in Hans Holderbach, *The CTBT - Legal Aspects of Its Implementation* (2006); available from http://www.vertic.org/assets/The_CTBT_-_Legal_Aspects_of_its_Implementation_Dubai_HH_May_06_1172.pdf.

[217] To enter into force, the CTBT must be signed and ratified by the 44 States listed in Annex 2 to the Treaty. These States formally participated in the work of the 1996 session of the Conference on Disarmament and possessed nuclear power or research reactors at that time. To date, 33 of the Annex 2 States have ratified the Treaty. So far, 175 States have signed the Treaty and 120 have deposited their instruments of ratification, of which 33 are States whose signature and ratification are necessary for the Treaty to enter into force.

[218] Albright and Hinderstein, "Uncovering the Nuclear Black Market: World toward Closing Gaps in the International Nonproliferation Regime". For more discussion about the role of intelligence in nuclear proliferation, see Phil Williams, "Intelligence and Nuclear Proliferation: Understanding and Probing Comlexity," review of Reviewed Item, *Strategic Insights*, no. 6 (2006).

in South Africa and the cases of Iran, Iraq, and Libya clearly show how important the early detection of programs though intelligence community activities is.

The UNSC, through the Military Staff Committee (MSC), can play an important role in facilitating cooperation among the international community. The MSC may provide access to the National Technical Means (NTM), in particular, military satellites for tracking the illicit shipment or transfer of nuclear elements according to Article 45 of UN Chapter VII.

B. Diplomatic Efforts

Successful cases of diplomatic efforts are often made by the U.S. In the mid-1970s, some major nuclear exporting states such as France and Germany were planning to transfer enrichment and reprocessing technology to South Korea, Taiwan, Pakistan and Brazil. The U.S. was very successful in stopping the spread of successful nuclear technologies in case of South Korea and Taiwan (in the 1970s and in 1987, respectively) by utilizing the leverage of high dependence of these countries on U.S. security and economic support. However, it was not successful in the case of Germany's provision of enrichment and reprocessing technology to Brazil.

C. Economic Efforts

Due to globalization, the economy of most states is integrated into the global economic system to varying degrees. Almost all states are reliant on foreign technology, the international financial system and international trade. Even though some proliferators such as Iran hold the "oil weapon", they can never be free from economic pressures from the international community. The case of Libya showed how economic efforts were successful. It became clear that Khadafy decided Libya could better assure its security through a positive relationship with the U.S. and the West than with a risky and costly policy of developing WMD. Libya's leaders thought that their nation's growing economic difficulties could be resolved only by redirecting resources into development, integrating closely into the world economy and seeing sanctions ended.[219] Table 5.6 shows possible measures of diplomatic and economic efforts; however, in this case, diplomatic and economic efforts were used together.

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[219] Tom Lantos, *Halting the Nuclear Black Market* (SFGate.com, Mar. 30 2004); available from <www.sfgate.com/cgi-bin/article.cgi?file=/chronicle/archive/2004/03/30/EDGL05T5KN1.DTL>.

Table 5.6 Cases of Multilateral and US-led Efforts

Classification	Description		Example
Economic options	**Sanctions**[220]	•Preventing the use of international financial system for conducting transactions -Preventing money transfers -Prohibition on granting loans and opening credit lines -Freezing of proliferators' assets abroad	North Korea, Iran, Iraq, Pakistan, South Africa
		•Preventing the acquisition of material or technology -Barring the dual-use items to proliferators -Embargoing advanced war materiel -Preventing participation in advanced studies -Halting IAEA technical assistance in the nuclear field -Restriction on the acquisition of specific items -Restriction on the acquisition of advanced technology	
Economic options	**Incentives**	• Economic incentives Nuclear Supply Assurances, financial benefit, nuclear technology transfer	North Korea. South Africa, Brazil, Argentina
Diplomatic options	**Pressures**	• US-led Diplomatic Pressure	South Korea, Taiwan, Iran
	Incentives	• Multilateral Talks	North Korea, Iran
		• Security Assurance Provision (i)United Nations Security Council resolutions 255 (1968) and 984 (1995); (ii)Effective international arrangements to assure non-nuclear- weapon States against the use or threat of use of nuclear weapons;	South Korea, Taiwan, Japan, NATO, Libya

5.11.2 Multilateral Military Efforts

A. Military Actions

Military options are always considered if a proliferator seeks a nuclear weapons program despite peaceful international efforts. Military options should be the last measure to deal with a proliferator due to possible negative consequences. In this case, legality issues may arise in executing multilateral

[220] Aharon Zeevi Farkash, *Iranian Strategic Vulnerabilities: Implications for Policy Options to Halt the Iranian Nuclear Program* (Jerusalem Center for Public Affairs); available from http://www.jcpa.org/text/iran_page_38-43.pdf.. Economic sanctions include trade wars, and economic warfare and financial restrictions (Mostly through authorization by UNSC). Robert A. Pape, "Why Economic Sanctions Do Not Work?," *International Security* 22, no. 2 (Autumn 1997).

efforts. The UN Charter Chapter VII, Article 51 provides the right to take military action for self-defense either individually or collectively, until the UNSC has taken measures necessary. [221]

A group of states or an individual state can use military efforts in anticipation of justification of their actions pursuant to Article 51. Israel's action in attacking and destroying the Syrian nuclear facility on September 6, 2007 was almost certainly a breach of international law, whether the facility was for military purposes or civilian purposes.[222] As Syria had not yet attacked Israel, any justification for Israel's use of force pursuant to Article 51 must have been found, if at all, by resort to the principle of anticipatory self-defense.[223]

Possible multilateral military options can be military strikes, military augmentation, or military withdrawal. Flournoy (1993) suggests deterrence, preventive war,[224] preemption, and defense as possible U.S. military options in dealing with nuclear proliferation. He also stresses the importance of declaratory policy and political support for U.S. military options.[225]

Saunders (2003) provides possible military options in case of a nuclear proliferation crisis at tactical level. [226] Generally, there are three issues when military strike option is considered:

- Locating all facilities and fissile material stocks that could be used in a nuclear weapons program;
- Possessing the capability to destroy these targets; and
- Preventing a proliferator from military retaliation with artillery fire, missiles strikes, chemical or biological weapons use, escalation to a full-scale conventional war, or nuclear weapons.[227]

B. Proliferation Security Initiative (PSI)

On May 31, 2003 President Bush announced the Proliferation Security Initiative (PSI), which is a global initiative aimed at stopping shipments of weapons of mass destruction (WMD), their delivery systems, and related materials worldwide. The PSI can work as a means to complement existing export

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[221] This article has been cited as support the legality of the Vietnam War.

[222] Article 2(4) of the United Nations Charter prohibits uses of force "against the territorial integrity" of any other state. States retain the inherent right of self-defense as defined in Article 51 of the Charter. Article 51 allows unilateral acts of force in self-defense on a temporary basis "if an armed attack occurs" against a member of the United Nations.

[223] Daniel Joyner, "North Korean Links to Building of a Nuclear Reactor in Syria," *Implications for International Law* 12, no. 8 (2008).

[224] For more discussion on "preventive war", see Jeffrey Record, "Nuclear Deterrence, Preventive War, and Counterproliferation," *Policy Analysis* 519 (2004).

[225] Michele A. Flournoy, "Chapter 6. Implications for U.S. Military Strategy," in *New Nuclear Nations: Consequences for U.S. Policy*, ed. Robert D. Blackwell and Albert Carnesale (New York, NY: The Council on Foreign Relations, 1993). Philip Zelikov, "Chapter 7. Offensive Military Options," in *New Nuclear Nations: Consequences for U.S. Policy*, ed. Robert D. Blackwell and Albert Carnesale (New York, NY: The Council on Foreign Relations, 1993)., pp.162-195. He suggests three sets of variables (timing and context for offensive action, the nature of adversary, the targeting objectives) for the use of military force to eliminate the danger of nuclear proliferation and explains some strategic issues including risks of military operations.

[226]Philip C. Saunders, *North Korea Special Collection: Military Options for Dealing with North Korea's Nuclear Program* (2003); available from http://cns.miis.edu/north_korea/dprkmil.htm.

[227] The last factor should be carefully reviewed during analysis process for adopting military options. In addition, Iran had the largest combined oil and gas reserve in the world and it may try economic retaliation using 'oil embargo' that can lead to the world economy depression.

control systems because it provides the international community with an effective means to take physical actions that support UNSC 1540 (2004) by interdicting illicit shipment or transfer of WMD-related components. The PSI can be interpreted as multilateral military efforts for nuclear nonproliferation; however, the Initiative's action is not an engagement but rather a preemptive measure.

The PSI has carried out three kinds of activity in order to strengthen its capabilities; (1) interdiction operations, (2) interdiction exercises, and (3) Operation Expert Group (OEG) meetings.[228] The PSI has been credited with the seizure of the centrifuge components on the BBC China, which resulted in the renouncement of the Libyan clandestine nuclear weapons program. The development of information sharing and arrangements for practical operation though the PSI has the potential to make a very important contribution to the effective enforcement of export controls.

One of the challenges of the PSI is that it has no legal background. The PSI is a set of activities, neither a formal treaty-based organization nor arrangements and agreements. Furthermore, in accordance with ***the Sea Convention***, the Initiative is in conflict with ***the right of innocent passage***, which gives the ships the rights of freedom of seas and innocent passage. In this regard, the PSI cannot alone fix the fundamental weaknesses of the current MECRs exposed by the discovery of the Khan network.

5.12 Laws and Systems of Participating States (The U.S. Case)

International treaties or agreements should be reflected into legislation in order to have robust legal effects from the perspective of international law. It takes a while for international treaties to have legal effects in member states and in the international community.[229] Even though international treaties are legislated, they will be practically effective only after a national system to fulfill treaty requirement is set up. It takes also time to settle administrative procedures for implementation.[230] In particular, national export control systems should be established in a way that can be harmonized with MECRs.

In this study, the U.S. national system for nonproliferation is studied because the U.S. has a well-organized legal framework to control illicit trade of nuclear elements. The U.S. governmental organizations that work for nuclear non-proliferation include the Nuclear Regulatory Committee (NRC), Department of Commerce (DOC), Department of Defense (DOD), Department of State (DOS), Department of Energy (DOE), Central Intelligence Agency (CIA), and National Security Council (NSC). Specific roles are explained in *Appendix*. However, it should be noted that the strong will of

[228] Operational Expert Group (OEG) meetings, which are meetings of enforcement officers, can be regarded as a kind of steering committee for the PSI. The OEG meetings are an opportunity for core PSI participants to work on information sharing arrangements and operational concepts for interdictions based on the experience gained in actual operations and exercises. Ian Anthony, Christer Ahlström, and Vitaly Fedchenko, *Reforming Nuclear Export Control: The Future of the Nuclear Suppliers Group* (New York: 2007: Oxford University Press Inc. , 2007)., pp.109-111.
[229] Sharon Hanson, *Legal Method & Reasoning*, 2nd ed. (London, U.K.: Cavendish Publishing Co., 2003)., pp.115-117.
[230] Sabatier and Mazmanian, "Chapter 1. The Implementation of Public Policy: A Framework of Analysis."

states to comply with the NPT regime is critical to preventing nuclear proliferation. All supplier states may be occasionally tempted to sell nuclear-related items for economic and/or political reasons.

5.13 Quantification of the NPT regime effectiveness

5.13.1 Walsh' Approach

Before the nuclear nonproliferation treaty (NPT) was negotiated in the 1960s, it was widely assumed that proliferation is inevitable and about 25 states would have nuclear weapons capability by the end of twentieth century.[231] In this context, the NPT is often considered to be a success in a sense that only three states have proliferated nuclear weapons after the NPT entered into force. Walsh (2006) argues that the success of the NPT is being largely ignored despite the NPT's contribution to nuclear nonproliferation. He further claims that the nuclear nonproliferation regime was one of the biggest and unheralded public policy achievements in the twentieth century.[232] This argument brings up the need of quantitative methods to measure whether the NPT regime has been successful or not.

Walsh (2006) also suggests that there are three standards in measuring success and failure of the NPT regime: the perfection standard, the pragmatists' standard, and comparative performance standard. He argues that 75% of countries that could have become nuclear weapons states decided to remain non-nuclear weapons states.[233] The effectiveness of the NPT regime can be quantified using his argument as follows:

$$Effectivess_{NPT} = 1 - \frac{Number\ of\ States\ Acquired\ Nuclear\ Weapons}{Number\ of\ States\ with\ Potential\ Nuclear\ Capability} = 1 - \frac{8}{32} = 0.75 \cdots (5.2)$$

5.13.2 Helm and Sprinz's Approach

The concept of regime effectiveness in international environmental regimes developed by Helm and Sprinz (2000) may be applicable to measure the effectiveness of nuclear nonproliferation because verification technologies are important factors in the success of regimes in both NPT regime and international environmental regimes. Some may argue that a direct application of this method to the NPT regime because this method is developed in the study of international environmental regimes, which has very different features from the NPT regime. First, the amount of environmental pollution can be quantified in a continuous fashion, whereas the nuclear proliferation is binary. Second, the

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[231] John Carlson, Russell Leslie, and Annette Berriman, "Strengthening the Non-Proliferation Regime" (paper presented at the 44th Annual Meeting of the INMM, Phoenix, AZ, July 13-17 2003).
[232] Jim Walsh, "Learning from Past Success: The NPT and the Future of Non-Proliferation" (paper presented at the The Weapons of Mass Destruction Commission, Stockholm, Sweden, Oct. 2005).
[233] Ibid. He only provides the list of 24 potential nuclear weapons states that remained non-nuclear. Having considered that only 8 states had successfully detonated nuclear weapons (in his case, he excluded North Korea), eight states out of a total of 32 states gives the number that only 25 percent of states with nuclear weapons states actually obtained nuclear weapons capability.

impact of environmental pollution is steady, whilst that of nuclear proliferation is volatile. However, this review has some values that the effectiveness of the NPT regime may be quantified despite its possible flaws.

The concept of ***perfect standard*** discussed by Walsh (2006) is used, the effectiveness score of the NPT regime can be obtained in the following:

- Collective optimum: no country has acquired since the NPT (i.e., perfect standard)
- Non-regime counterfactual: the number of states that would have acquired these weapons without the NPT
- Actual performance: the number of states that has acquired a nuclear weapons capability.

We can assume that the non-regime counterfactual is 25 and actual performance is 4. This is based on the fact that India, Israel, Pakistan, and North Korea have acquired nuclear weapons capability. The effectiveness of the current NPT regime (E_{NPT}) can be obtained with equation above

$$E_{NPT} = \frac{AP - NR}{CO - NR} = \frac{4-25}{0-25} = 0.84 \quad \cdots\cdots(5.3)$$

5.13.3 Competitive Approach

Figure 5.8 shows the relationship between the states that successfully tested nuclear weapons and the newly-introduced NPT regime components over time. It seems that there were four nuclear arms race periods from the 1940s to the 2000s including the one that we are facing now. If the slopes for each period are compared, they appear to go down and the NPT regime seems to be very effective in the 1980s and 1990s. However, in assessing whether the NPT regime has been effective, two time factors should considered. First, some delays should be considered between the time when a new NPT regime component was introduced and when it became effective as a practical method. Second, it takes a while to complete a nuclear weapons program as noted in Chapters 3 and 4. In this regard, even though the figure seems to show that the NPT regime was effective in the 1980s and 1990s, it cannot be obviously said that the NPT regime was really effective.

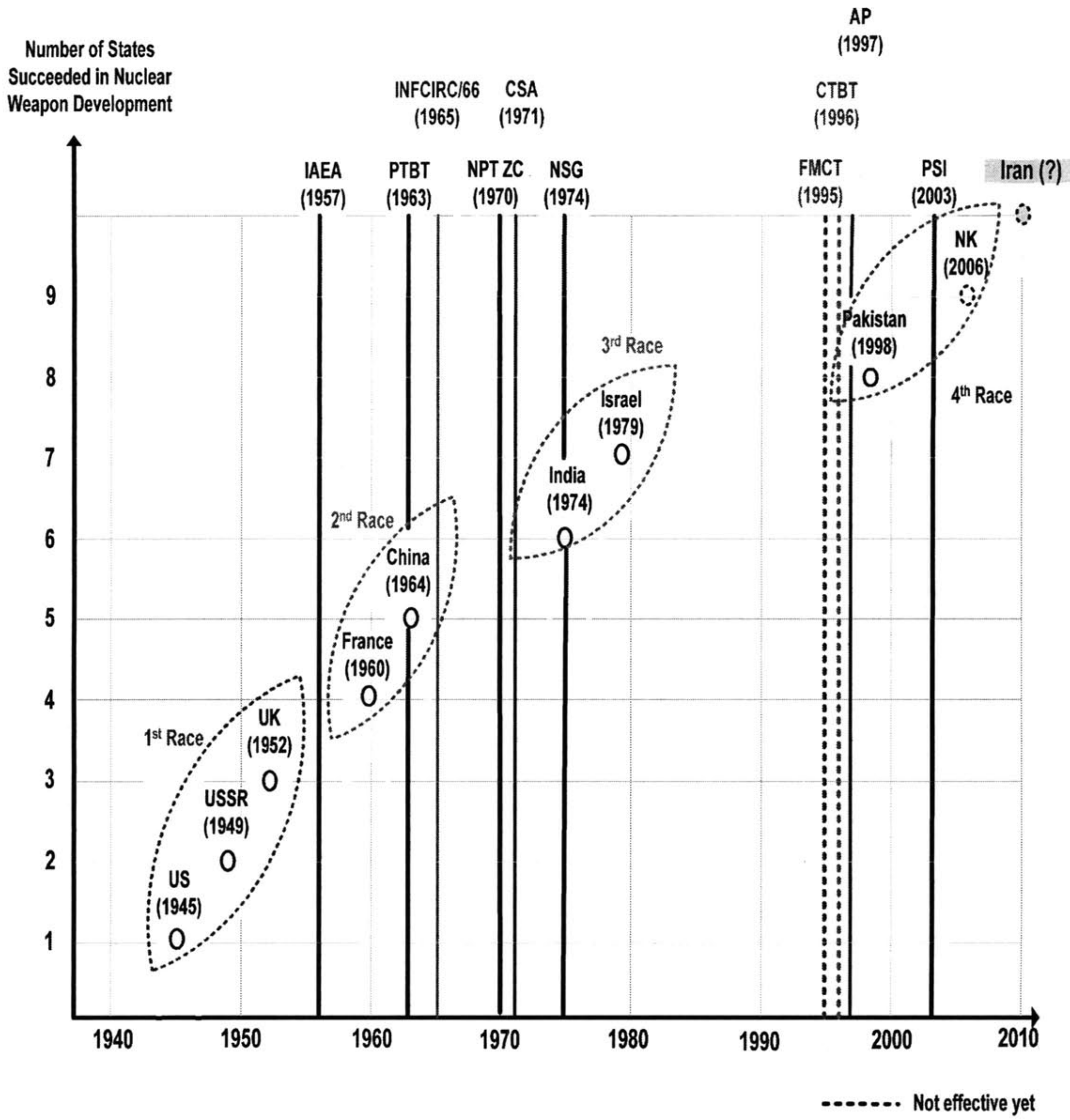

Figure 5.8 Nuclear Proliferation and the NPT Regime over Time

5.14 Resources of the NPT Regime

5.14.1 Implementation Resources of the NPT regime

Implementation resources of the NPT regime can be interpreted as the combination of membership of NPT regime components and domestic efforts to reflect those components in the form of legislation. However, only membership of the main components in the NPT regime is shown in Table 5.7 because domestic efforts are state-specific and beyond the scope of this study.

Table 5.7 Membership Status of Main Players in the NPT Regime

Country	NPT	Treaty		MECRs			Multilateral Cooperation
		NWFZ [a]	CTBT [b]	ZC [c]	NSG [d]	WA [e]	PSI [f]
Argentina	X	X	X	X	X	X	X
Australia	X	X	X	X	X	X	X
Brazil	X	X	X		X		
China	X		X	X	X		
France	X		X	X	X	X	X
India			X				
Iran	X		X				
Israel			X				X
North Korea							
Pakistan			X				
Russia	X			X	X	X	X
South Africa	X	X	X	X	X	X	X
South Korea	X		X	X	X	X	
Sweden	X		X	X	X	X	X
U.K.	X		X	X	X	X	X
US	X		X	X	X	X	X

Notes
[a]. Australia Treaty of Rarotonga of 1985, Treaty of Tlatelolco of 1967, Treaty of Pelindaba of 1964
[b]. CTBT: <http://www.ctbto.org/fileadmin/user_upload/procurement/CTBTO_Member_States.doc
[c]. ZC: <http://www.zanggercommittee.org/Zangger/Members/default.htm>
[d]. NSG: <http://www.nuclearsuppliersgroup.org/member.htm>
[e]. WA: <http://www.wassenaar.org/participants/index.html>
[f]. PSI: <http://www.state.gov/t/isn/c27732.htm>
[g] X denotes that the country has membership in the NPT regime component.

5.14.2 Verification Resources of the NPT Regime

The NPT regime continues to face a shortage of verification resources. The IAEA is the only component that has verification resources. The NPT regime's verification resources fail to keep pace with the increasing verification demand because of the development and spread of nuclear technology. The dual characteristic of nuclear energy technology continuously poses an additional challenge to the NPT regime. The IAEA has been developing a system to optimize the use of its limited resources such as the Integrated Safeguards System (ISS) and information analysis system.

5.14.3 Compliance-Enforcement Resources of the NPT Regime

The NPT regime does not have explicit compliance-enforcing resources. And most nonproliferation regime components are not legally-binding. As a result, the use of correcting or punishing measures is very limited in the NPT regime, which can be regarded as the weakest point of the NPT regime. For example, the NPT has no enforcement clause; therefore, the NPT provides no penalties for quitting or violating the treaty. As a partial solution, the UNSC can provide compliance-enforcing resources if the IAEA requests. In the case of non-compliance in the NPT regime, a variety of response measures are available by the UNSC, ranging from diplomatic, economic to military measures. The policy choice between economic sanctions and military coercion crosscuts the theoretical divide in international relations theory between liberal insitutionalism and realism.[234] Table 5.8 shows the available resources of all the NPT regime components.

Table 5.8 Summary the NPT Regime's Resources

Classification		Implementation Resources	Verification Resources	Compliance-Enforcement Resources
Treaty	NPT	O	Δ	-
International Organization	IAEA	O	O	Δ
	UNSC	O	Δ	O
	UN	Δ		Δ
MECRs	NSG, WA, ZC	Δ		-
Multilateral Cooperation	PSI	Δ	Δ	-
	Intelligence community	-	Δ	-
	Diplomatic cooperation	Δ	-	Δ
Domestic systems	Laws and systems	O	Δ	Δ
Complementary Treaties	FMCT	Δ	Possibly IAEA[235]	N/A
	CTBT	Δ	CTBTO	N/A
	NWFZ	Δ	Δ	Δ

Notes
[a] O and Δ denote direct possession and indirect possession, respectively.
[b] FMCT and CTBT are not effective yet and NWFZ is applied only in the region where it is established.

5.15. Capabilities of the NPT Regime

The IAEA defines that the safeguards system consists of "three, interrelated elements: (i) the Agency's statutory authority to establish and administer safeguards; (ii) the rights and obligations assumed in safeguards agreements and additional protocols; and (iii) the technical measures implemented pursuant

[234] Pape, "Why Economic Sanctions Do Not Work?."
[235] Hui Zhang, "Should and Can the FMCT Be Effectively Verified?," *INESAP Information Bulletin* 28 (April 2008).

to those agreements." [236] John Carlson et al., (2006) [237] suggest that the IAEA's safeguards capabilities can be considered in two broad categories, technical and legal. The next step for this paper, then, is to conceptualize the legal and technical capabilities of components of regimes in relation to resources of regimes. In this paper, John Carlson et al. (2006)'s view is used and is defined as follows.

• Legal capabilities – organization's statutory authority to exercise its legal rights and responsibilities
• Technical capabilities – technical measures and technical expertise to conduct verification activities

The capabilities of all NPT regime components can be analyzed using this framework and Figure 5.9 and Table 5.9 show the analysis of the capabilities. However, it should be noted that they are dependent upon each other.

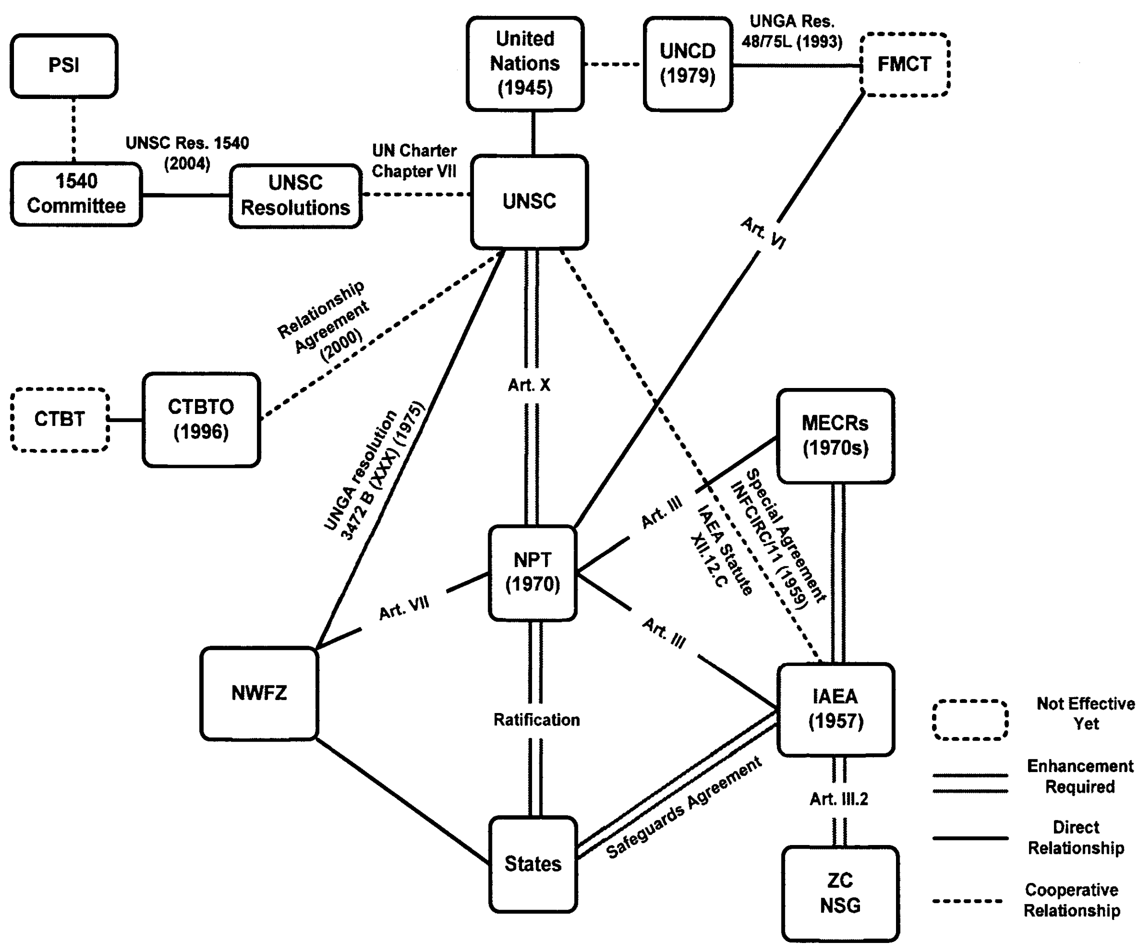

Figure 5.9 Legal Framework of the NPT Regime via the NPT

236 "INFCIRC/640, Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report Submitted to the Director General of the IAEA," (Vienna, Austria: IAEA, Feb. 2005).
237 Carlson and Leslie, "Safeguards Intensity as a Function of Safeguards Status".

Table 5.9 Capabilities of NPT Regime Components

Components		Legal capabilities	Technical capabilities
International organizations	IAEA	• NPT • Safeguards agreements	• Safeguards techniques
	UNSC	• Resolutions under the UN Charter Chapter VII • UNSC 1540 Committee	N/A
	UNGA	• UN Charter and UNGA resolution 377 (V) of 1950	N/A
MECRs	NSG, WA, ZC	• Authorization systems of member states • International cooperation system	• Information analysis
Multilateral Cooperation	PSI	• Interdiction operations	N/A
	Intelligence community	• Information collection and sharing	• National Technical Means (NTMs)
	Diplomatic cooperation	• Incentives, sanctions and pressures	N/A
Domestic systems	Legislation and system	• National export control system • Systems of Accounting for and Control of Nuclear Material (SSAC)	• Border control system • Physical protection system
Complementary Treaties	FMCT	• International treaty	• Similar to safeguards
	CTBT	• International treaty	• International Monitoring System • Data Analysis System
	NWFZ	• NPT and UN	•Similar to safeguards

5.16 Conclusion

A regime theory and its application to the NPT regime, the components of the NPT regime, and a theoretical approach to evaluate the power and effectiveness of the NPT regime at international level were reviewed. For the evaluation of the effectiveness of the NPT regime, both quantitative and qualitative ways were studied. There have been a number of disputes about whether the NPT regime has been really effective. However, the study showed that the NPT regime contributed to the deterrence of potential proliferators from proliferating.

Reviewing the evolution of the NPT regime, most non-proliferation measures were implemented after nuclear proliferation events had occurred. In addition, there was a delay for a newly-introduced NPT regime component to become effective. Therefore, the development of analytical tools for evaluating the NPT regime will be helpful when developing policies to prevent future nuclear proliferation. This tool would help analyze strengths and weaknesses of the NPT regime to prevent, or at least, deter nuclear proliferation.

CHAPTER 6 OVERVIEW OF IAEA SAFEGUARDS

6.1 Introduction

Article III of the Nuclear Nonproliferation Treaty (NPT) requires each member state to conclude a safeguards agreement with the IAEA.[238] The NPT entitles the IAEA to verify that no member state is in violation of the NPT in order to assure the international community. The IAEA should have enough capabilities to verify states' declarations and to detect undeclared facilities or activities. Among various systems in the IAEA, IAEA safeguards system is a means for verification and it encompasses the Agency's statutory authority, the rights and obligations, and technical measures for verification. If safeguards cannot detect proliferation activities, the NPT regime will collapse.

In this regard, it is critical to understand the capabilities of the IAEA safeguards. However, the IAEA has several types of safeguards, specific to each member state. Because different safeguards types provide different capabilities to the IAEA, the IAEA's capabilities will vary significantly depending on which types of safeguards agreements was concluded between the IAEA and each member state. In this study, the IAEA's safeguards capabilities is analyzed in terms of technical and legal capabilities.[239] This chapter will focus on the review of IAEA safeguards for legal capabilities.

6.2 The IAEA and Safeguards

The IAEA's legal basis for continuing safeguards activities is given by the NPT because the NPT mandates its member states to establish safeguard agreements with the IAEA. Without the NPT, key elements of nuclear fuel cycles would be excluded from safeguards coverage, although some nuclear facilities and materials would be still covered by only non-NPT safeguards.[240] IAEA Statute Article A.6 gives designated IAEA inspectors access and their inspection rights.

The IAEA's relationship with the UN is regulated by special agreement INFCIRC/11 signed on October 30, 1959.[241] In terms of its Statute, IAEA Statute XII, Agency Safeguards, the IAEA Board of

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[238] Each state party should commence the negotiation of IAEA safeguards agreements within 180 days from the entry into the NPT. Such agreements shall enter into force not later than 18 months after the date of initiation of negotiations.

[239] Carlson and Leslie, "Safeguards Intensity as a Function of Safeguards Status". Legal authority issues generally involve the IAEA's access to specific locations; the IAEA's access to particular information; and its right to question personnel. The IAEA's legal capability is to facilitate employment of particular safeguards measures. Issues of the IAEA's authority will concern the IAEA's right of access to specific locations. They can also relate to the IAEA's right to request particular information, and its right to question specific persons. Technical detection capability includes inspection capability and monitoring capability. There are some overlaps between techniques for inspection and monitoring activities such as satellite imagery and environmental sampling.

[240] Simpson and Howlett, "The NPT Renewal Conference: Stumbling toward 1995." Currently, the IAEA has 145 members, while the NPT has 189 member states.

[241] D.M. Edwards, "International Legal Aspects of Safeguards and the Non-Proliferation of Nuclear Weapons," *The International and Comparative Law Quarterly* 33, no. 1 (Jan. 1984).The UNGAs of 1954 and 1955 reached

Governors reports to the UNGA and to the UNSC regarding non-compliance by States with their safeguard obligations as well as on matters relating to international peace and security. The UNSC and IAEA are partners within the UN system and the UNSC has authority to empower the IAEA to act on its behalf to help the UNSC meet its obligations.

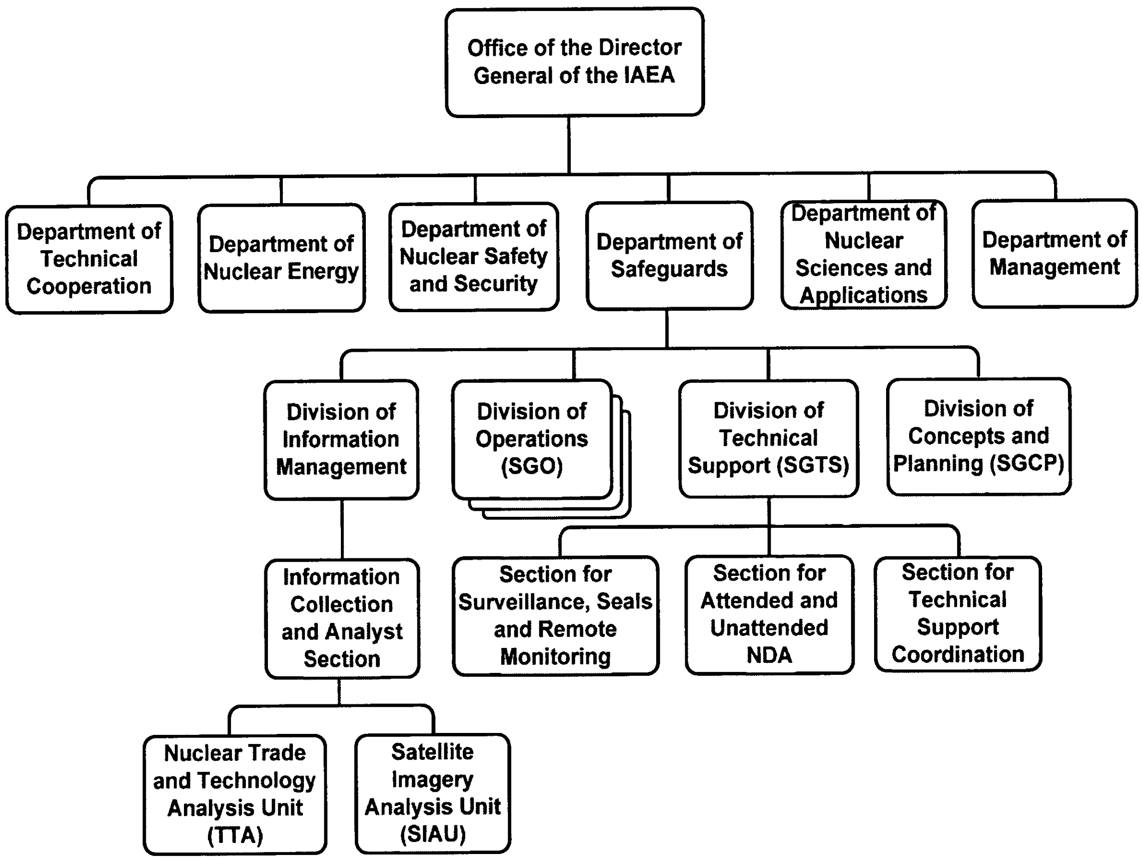


Figure 6.1 IAEA Organizational Chart

The IAEA has six departments as shown Figure 6.1, with the IAEA Department of Safeguards serving as organizational hub for the IAEA's safeguards work. Similar regional agencies are EURATOM and the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC) established through regional safeguards arrangements.

the view that the IAEA should not be a specialized agency of the UN but an autonomous organization with co-operative links with the UN and the various relevant UN organs.

6.3 Historical Background of IAEA Safeguards

The IAEA safeguards system[242] has evolved over time to deal properly with threats. The types of Safeguards Agreements currently available pursuant to the NPT are summarized in Table 6.1. All of these safeguards systems differ in the undertakings, the obligations and scope of IAEA verification activities.

Table 6.1 Types of IAEA Safeguards

Safeguards Title	IAEA Reference document	Since	Current Application
Item-(or facility) specific Safeguards Agreement	INFCIRC/66/Rev.2	1965 (before NPT)	Non-NPT Signatories
Comprehensive Safeguards Agreements (CSA) or Full-Scope Safeguards (FSS)	INFCIRC/153	1970 (after NPT)	NNWS of NPT member states
Voluntary Offer Agreements (VOA) [243]			NWS
Small Quantities Protocol (SQP)[244]		1974	NNWS[245]
Additional Protocol (AP)	INFCIRC/540	1997	All states with any type of safeguards agreement

In establishing safeguards agreements between states and the IAEA, the membership of the NPT, the nuclear status of states, i.e., Nuclear Weapons States (NWS) or Non-Nuclear Weapon States (NNWS), and the existence of significant nuclear activities are the factors that determine the type of safeguards that will be applied.

INFCIRC/66 was the original IAEA safeguards that existed before the NPT entered into force. After the entry into force of the NPT, INFCIRC/153 was introduced in order to deal with proliferation of nuclear weapons. As a result of the detection of Iraq's secret nuclear weapons program, "93+2

[242] Webster dictionary defines safeguard as a precautionary measure, stipulation, or device b: a technical contrivance to prevent accident. Lovett defines safeguards as "a collective term that comprises those measures designed to guard against the diversion of material such as source and special nuclear material from uses permitted by law or treaty, and to give timely indication of possible diversion or credible assurance that no diversion has occurred. James E. Lovett, *Nuclear Materials : Accountability, Management, Safeguards* ([Hinsdale, Ill.]: American Nuclear Society, 1974)..

[243] NWSs have entered into limited scope VOA (voluntary offer safeguards agreements) modeled in CSAs. These VOA agreements place no obligation on the state in relation to the nuclear materials to be subject to safeguards and they permit the state to withdraw nuclear materials and to remove facilities from the list designated by the state which the IAEA can select for the purposes of safeguards implementation.

[244]Russell Leslie, John Carlson, and Annette Berriman, "Ensuring Effective Safeguards Coverage of States with Small Quantities Protocols," *Australian Safeguards and Non-Proliferation Office* (2007).

[245] The standard text of SQP was first introduced in 1971, and was available to States which had ***less than specified quantities of nuclear material*** and no nuclear material in a nuclear facility. For such States, safeguards implementation is expected to be simple and straightforward. Small Quantities Protocol is designed to apply safeguards for most State parties to the NPT have no nuclear facilities and only limited quantities of nuclear material. (states with no significant nuclear activities)

program" was applied as a temporary measure to strengthen the IAEA's safeguards. The IAEA ended up the Additional Protocol (AP) to equip the IAEA with important new tools and systems for verification. However, the IAEA is still under scrutiny as to whether the Additional Protocol (AP) has sufficient authority and capabilities to deal with current proliferation challenges.

6.4 Facilities and Materials under Safeguards

6.4.1 IAEA Safeguards on Nuclear Fuel Cycle Facilities

The application of IAEA safeguards is undergoing development. Table 6.2 shows the evolution of safeguards for a variety of nuclear facilities in a nuclear fuel cycle.

Table 6.2 Nuclear Fuel Cycle Facilities and Safeguards Types Applied

Type of Facility	First recognition	First application of safeguards	Related Articles
Large Reactor Facilities	INFCIRC/26/Add.1 (1964)		All
Plutonium Reprocessing Facilities	INFCIRC/66/Rev.1 (1966)		Annex I
Uranium Conversion Facilities[246] [e]	INFCIRC/66/Rev.2 (1968)		Annex II
Fuel Fabrication Plants			
Separate Storage Installation			61-66
Isotope Separation Plants	INFCIRC/153/Corrected (1972)		106
Uranium Mines and Concentration Plants (U. Th)[247][d]	INFCIRC/66/Rev.2 (1968) [b]	INFCIRC/540[248]	2.a.(v) [c]
Location Outside Facilities (LOF)	Nuclear material outside facilities (INFCIRC/153)		49
	Operational status of LOF (INFCIRC/540)		2.a.(ii)

Notes
[a] 26 and 66 from http://www.iaea.org/Publications/Documents/Infcircs/Others/inf66r2.shtml
[b] This document mentions that a mine or an ore-processing plant is not under safeguards.
[c] The provision of this information does not require detailed NMA.
[d] Article 78. This plant is expressed as "Ore-Processing Plant" in INFCIRC/66/Rev.2
[e] The IAEA did not conduct verification measures at UCFs until the 2000s. Safeguards verification typically begins after the uranium conversion process at the head end of the facility.

246 K. E. Owen, "Implementation of IAEA Policy Paper 18 in Canada, IAEA-CN-148/39" (paper presented at the International Safeguards Symposium, Vienna, Austria, Oct. 16-20, 2006).; Jay Doo et al., "Safeguards Approach for Natural Uranium Conversion Plants" (paper presented at the 44th Annual Meeting of Institute of Nuclear Material Management, Phoenix, AZ, Jul 13-17 2003).

247 R. Scott Kemp, "On the Feasibility of Safeguarding Uranium Mines," *Nonproliferation Review* 13, no. 2 (Jul. 2006).

248 The Additional Protocol Article 2 (v) prescribes that "Information specifying the location, operational status and the estimated annual production capacity of uranium mines and concentration plants and thorium concentration plants, and the current annual production of such mines and concentration plants for .... as a whole. .... shall provide, upon request by the Agency, the current annual production of an individual mine or concentration plant. The provision of this information does not require detailed Nuclear Material Accountancy (NMA)."

Safeguards for large reactor facilities have the longest history of application. The IAEA has limited experience applying safeguards to sensitive nuclear facilities: PRFs and UEFs. Developing safeguards approaches for Uranium Enrichment Facilities (UEFs) and Plutonium Reprocessing Facilities (PRFs) are still on-going. The IAEA started the routine application of safeguards to PRFs since May 1977 and to UEFs since 1979 (at Almelo and Capenhurst). [249]

The weakest part in applying safeguards to nuclear fuel cycle is uranium mining and milling facilities. It is not easy to develop safeguards for these facilities that can achieve safeguards objectives.[250] The AP requires states to provide information about those facilities, but it still lacks capability to achieve the IAEA's safeguards objectives.

6.4.2 Materials under Safeguards

Article III.2 of the NPT tells each state party to the treaty undertakes not to provide nuclear material (i.e., special fissionable material and source material) to any NNWS for peaceful purposes, unless it is subject to safeguards. The IAEA safeguards provides guidelines what kinds of and how nuclear material is safeguarded because it is not possible to safeguard all types and quantities of nuclear materials. However, some of nuclear materials are not under safeguards and those are listed in Table 6.3. But it should be noted that exemptions of nuclear material from safeguards are not available unless material is first declared and agreed by the IAEA at the request of the state.

Table 6.3 Comparison of CSA and AP for Safeguards Application Concerning Nuclear Material

Classification	Description	CSA	AP [e]
Nuclear material	All source or special fissionable material in all peaceful nuclear activities within the territory of the state	O [2]	O
Source material	Other than Uranium Ore Concentrate (UOC)	O [2]	O
	Uranium Ore Concentrate (UOC)	X [34]	*O [2a(vi)(a)]*
	International transfer of UOC for non-nuclear purposes [f]	X [34(a)(b)]	O [2a(vi)]

(Continued)

[249] IAEA, "The Present Status of IAEA Safeguards on Nuclear Fuel Cycle Facilities," *IAEA Bulletin* 22, no. 3/4 (1980). This document states that the IAEA had three enrichment plants under safeguards in 1980 under an ad-hoc regime. The IAEA started applying safeguards on a routine basis at the URENCO and Japanese facilities soon after completion of the Hexapartite Safeguards Project (HSP) in 1983. The details about HSP are available in chapter 10.

[250] Kemp, "On the Feasibility of Safeguarding Uranium Mines.".

Exemption from safeguards	Special fissionable material used in gram quantities or less	X [36.(a)]	X
	Used in non-nuclear activities in a non-nuclear end-use form	X [36.(b)]	*O [2.a.(vii)]*
	Plutonium with an isotopic concentration of Pu-238 exceeding 80%	X [36.(c)]	X
	One kg in total of special fissionable material	X [37.(a)]	*O [2.a.(vii)]*
	Ten metric tons of NU and DU with an UER 0.5%	X [37.(b)]	*O [2.a.(vi)]*
	Twenty metric tons of DU with an UER 0.5% or below	X [37.(c)]	*O [2.a.(vi)]*
	Twenty metric tons of thorium	X [37.(d)]	*O [2.a.(vi)]*
Termination	Consumed or diluted nuclear material, which has become practically irrecoverable	X [11, 35]	X [2a(viii)]
Re-application of safeguards	Exempted material is to be processed or stored together with safeguarded nuclear material	O [38]	O
	Further processing of intermediate or high-level waste containing plutonium	X	O [2.a.(viii)]

Notes

[a] X and O (in green boxes) stand for "subject to safeguards" and "not subject to safeguards," respectively.

[b] Nuclear materials in a non-nuclear end-use form means that it has not reached to the composition and purity suitable for fuel fabrication or for being isotopically enriched)

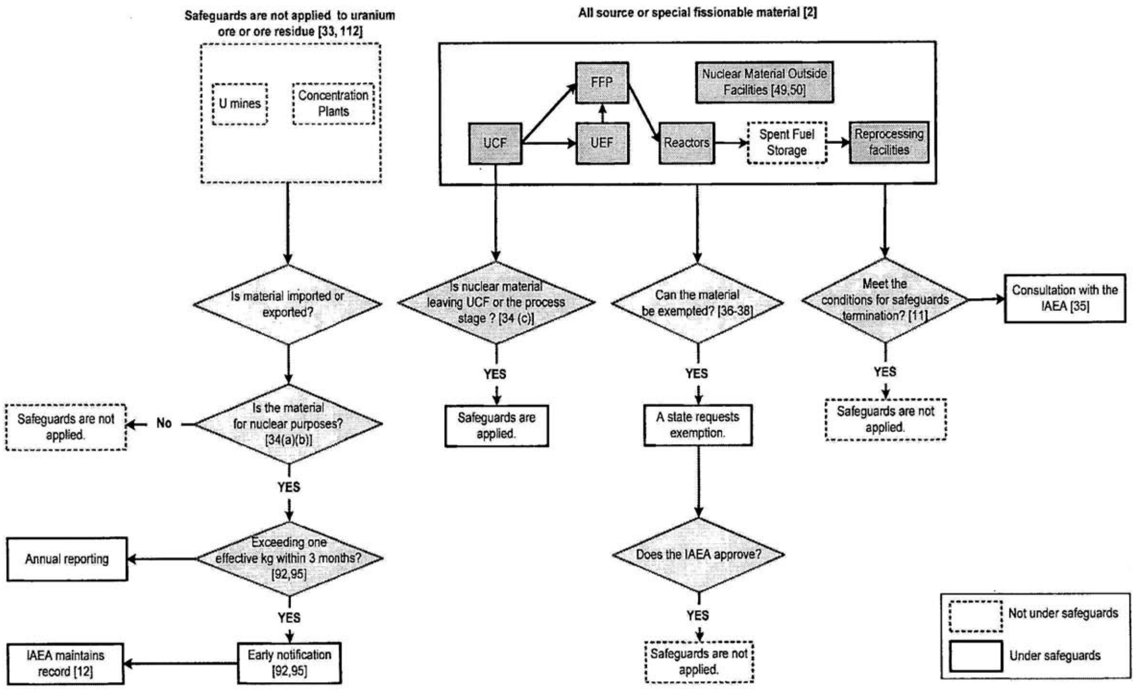
[c] *Italic* (in yellow boxes) means that the provision of information does not require detailed Nuclear Material Accountancy (NMA).

[d] Numbers in parentheses refer to articles and paragraphs in the AP and CSA, respectively.

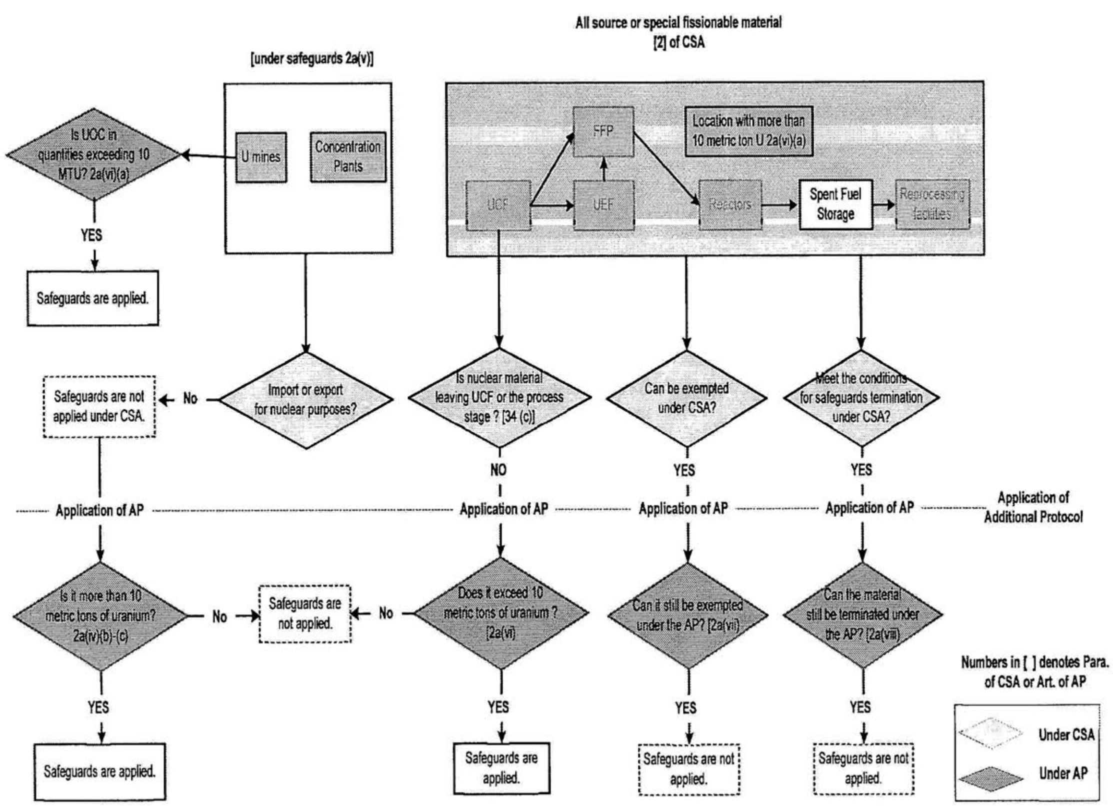
[e] The quantities and detailed NMA requirement for reporting should be referred to INFCIRC/540.

[f] For example, uranium in phosphate ore for manufacture of fertilizer.

Figure 6.2 presents a flow chart describing the applicability of safeguards for different types of nuclear materials and facilities covered under the CSA and the AP. The chart is useful in understanding under which circumstances safeguards are not applied.



(a) Under Comprehensive Safeguards Agreement



(b) Under Additional Protocol with Comprehensive Safeguards Agreement

Figure 6.2 Flow Chart for Safeguards Application under CSA and AP

6.5 Types of IAEA Safeguards

There are several types of safeguard regimes in existence. These include: INFCIRC/66, INFCIRC/153, INFCIRC/153 coupled with INFCIRC/540, and Integrated Safeguards (IS). In general, only one of these safeguard regimes applies to a given member state at any given time. The following will provide a general background for understanding IAEA's safeguard regimes.

6.5.1 INFCIRC/66

INFCIRC/66 was established before the NPT entered into force.[251] India, Israel, and Pakistan, which are not state parties to the NPT, have this type of safeguards agreement with the IAEA. This is a partial safeguards applied since 1965. It requires a state to report to the IAEA about its stockpile and provides access to limited nuclear facilities declared by a state. However, this type of safeguards only applied to fuel manufacturing plants. INFCIRC/66 was provisionally extended in 1966 and 1968 as INFCIRC/66/Rev.1 and INFCIRC/66/Rev.2. INFCIRC/66/Rev.1 was published to provide additional provisions for reprocessing plants and INFCIRC/66/Rev.2 was to provide further provisions for safeguarded nuclear material in uranium conversion plants and fuel fabrication plants.

6.5.2 INFCIRC/153 (Comprehensive Safeguards Agreements)

INFCIRC/153 type safeguards is the most common type of safeguards, and this type is called comprehensive safeguards agreement (CSA) or full-scope safeguards (FSS) system. INFCIRC/153 is designed to focus on Nuclear Material Accountancy (NMA), and it provides the IAEA with the right and obligation to ensure safeguards are applied to all nuclear material through inspection activities.

A. Authority of the IAEA

The objective of INFCIRC/153 agreements is to confirm the ***correctness*** of states' declarations in terms of nuclear material through the timely detection of any diversion of significant quantities[252] of nuclear material as declared by the state from peaceful nuclear activities to the manufacture of nuclear weapons or other nuclear explosives, or for any other purpose.

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[251] However, this type of safeguards is still legally binding. Para 4 of Article I.A. of INFCIRC/66/Rev.2 states that "*Provision of this document...will only become legally binding upon the entry into force of a safeguards agreement.....*"

[252] Timely detection and significant quantity are noteworthy in the statement. The IAEA set the timeliness goal to prevent proliferators from diverting material into nuclear weapons manufacture. The IAEA also defines a significant quantity as "The approximate quantity of nuclear material in respect of which, taking into account any conversion process involved, the possibility of manufacturing a nuclear explosive device cannot be excluded." The quantities given which are relevant to an enrichment plant are 25 kg of U-235 in uranium enriched to 20 per cent or more, highly enriched uranium (HEU), and 75 kg of U-235enriched to lower values, low-enriched uranium. The difference in mass is due to the assumption that the conversion process difficulty in enriching to weapon-grade levels.

B. Undertakings of States

INFCIRC/153 requires all members to create a State System of Accounting for and Control of its nuclear material (SSAC), to be responsible for implementing effective accountancy arrangements, and to control imports and exports of nuclear material,[253] coupled with a Voluntary Reporting Scheme (VRS) of 1993 whose components are incorporated in the AP. INFCIRC/153 greatly strengthened the capabilities and authority of the IAEA. However, the limitations of INFCIRC/153 should be clearly and carefully understood. Often, IAEA's authority based on INFCIRC/153 type is not understood correctly owing to its name, full-scope safeguards. It requires additional measures to enhance IAEA's safeguarding capacities because it is only focused on material diversion at declared facilities. Limitations caused by focusing on nuclear material are in the following:

C. Limitations of the CSA

Despite the authority given to the IAEA, the CSA allows only limited access to limited facilities and poses some problems. First, the application of safeguards is limited to nuclear material. Therefore, inspection activities cannot be performed at facilities that have nothing to do with nuclear material such as a nuclear weapon design program or manufacturing facilities for equivalent to a weapon and clandestine facilities not declared by a state. Second, full-access is not given to IAEA inspectors at declared facilities. Even at declared facilities that are related to NMA, locations open to inspection activities are limited to particular points where nuclear material is expected to flow (i.e., strategic or key measuring points) [254]. Third, the IAEA has very limited means to resolve any issues in the event that NMA is not correct. Even though a ***special inspection*** can be used under INFCIRC/153, few have been invoked because neither the IAEA nor the states on the BOG wanted to raise any politically delicate doubts about either the reliability of CSA or the honesty of some NPT parties.[255] Fourth, under the CSA, safeguards do not involve any specific measures for detection of undeclared feed or the undeclared product and tails that might be produced from it. Hence, INFCIRC-153 safeguards are not able to cover detection of clandestine acquisition activities. Finally, the IAEA allocated its safeguard resources purely based on the size of the nuclear fuel cycle, which resulted in the concentration of its effort on the highly

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[253] Under CSAs, States are required to declare the types and quantities of material subject to safeguards in an initial report on nuclear material. Any subsequent import or export of nuclear material is also to be reported, this may be done in a consolidated annual report.

[254] For access for inspections, please refer to paragraph 76 (c) and (d) of INFCIRC/153.

[255] The IAEA invoked the special inspection provision on two occasions: Romania in 1992 and North Korea in 1993. The IAEA conducted Romanian inspection and Romania actually asked to be inspected to build confidence that it had abandoned the Ceausescu regime's nuclear weapons program. But, North Korea refused to allow it.James M. Acton, Mark Fitzpatrick, and Pierre Goldschmidt, *The Iaes Should Call for a Special Inspection in Syria.* (Carnegic Endowment for Internatioal Peace, Feb. 26 2009 [cited Mar. 15 2009]); available from <http://www.carnegieendowment.org/publications/index/cfm?fa=view&id=22791>.. For more information concerning procedures, refer to Paragraphs 73, 77, and 83 (b) of INFCIRC/153.

developed countries with large fuel cycle facilities. Consequently, few resources were allocated for unpredictable countries with declared fuel cycle of small size.[256]

6.5.3 Additional Protocols (INFCIRC/540)

INFCIRC/540 type safeguards are called the Additional Protocol (AP) to the Agreement. The term Strengthened Safeguards System (SSS) is used for the combination of the CSA and the AP. This type of safeguards was developed in a response to lessons learned from the case of Iraq. Iraq was an NPT state subject to a CSA, but the IAEA did not discover an extensive clandestine nuclear weapons program in Iraq until it was made known after the Gulf War. It led the IAEA to conclude that the CSA, which concentrates on verifying nuclear material accountancy (NMA) only at facilities declared by a State, was inadequate. The IAEA Board of Governors (BOG) requested that its Standing Advisory Group on Safeguards Implementation (SAGSI) propose ways to strengthen safeguards system of the IAEA.

A. Authority of the IAEA

The objective of INFCIRC/540 is to confirm the ***completeness*** as well as the ***correctness*** of state declarations by demonstrating the absence of undeclared nuclear material/activities. In this regard, INFCIRC/540 requires new verification methods and technologies, including information collection and analysis, advanced environmental sampling, and the use of satellite imagery. The AP improved capabilities to detect undeclared production of fissile materials on the one hand, but the legal provisions and the methods to be applied will require several years for full implementation. The AP's major justification is to verify the absence of undeclared nuclear material/activities and the ***completeness*** of state declarations.

From many perspectives, the AP empowers IAEA inspectors to achieve safeguards objectives with enhanced detection capability and legal authority. The most important feature of the AP for verification is *complementary access* given to inspectors. According to complementary access, IAEA inspectors can be given unlimited and intrusive access - the ability to inspect any location where undeclared nuclear activities or suspicious activities might be going on, at least theoretically. However, unlike a special inspection under the CSA, complementary access is regarded as a common process under the AP for resolving any inconsistencies, without causing any political sensitiveness. Figure 6.3 shows the enhanced verification authority of the IAEA through the AP.

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[256] About 75 per cent of the routine and ad hoc inspections were conducted in Germany, Japan and Canada. Wolfgang Fischer and Gotthard Stein, "On-Site Inspections: Experience from Nuclear Safeguarding," *Disarmament Forum* Three (1999).

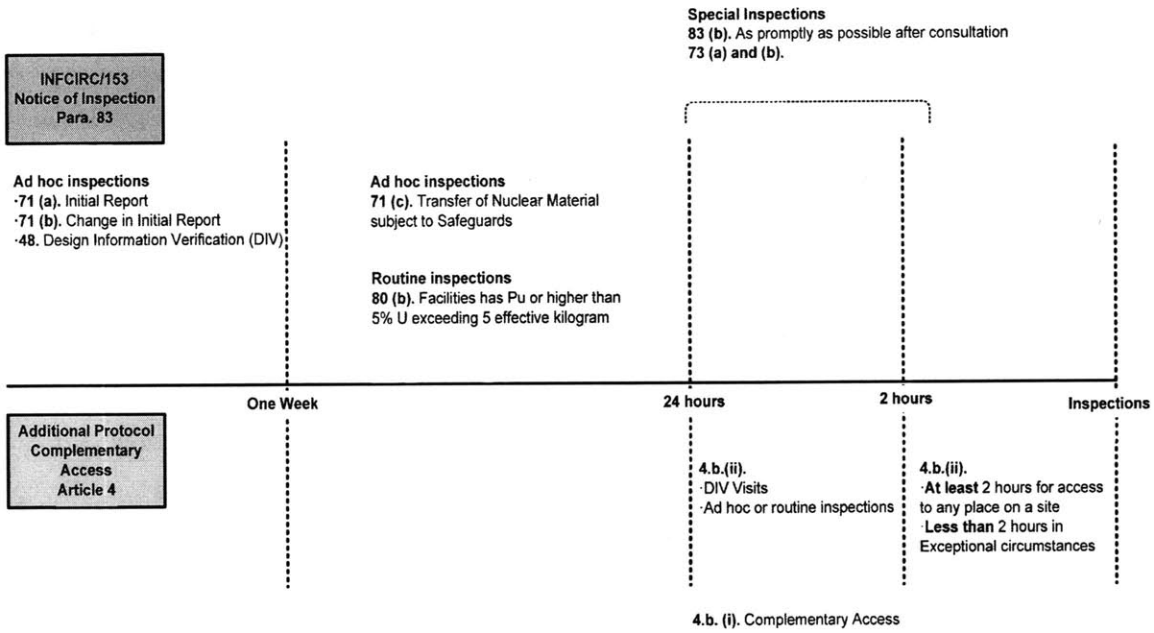

Figure 6.3 Notice Requirements for Inspections under CSA and AP

B. Undertakings of States

As IAEA inspectors' authority increases, states with the AP in force should provide more extensive information to the IAEA than with only the CSA. Under the CSA, the Voluntary Reporting Scheme (VRS), which was endorsed by the BOG in 1993, is not mandatory. However, it is incorporated in the AP as a mandatory feature for providing extensive information to the IAEA.

C. Limitations

There exist limitations in the application of the AP from the standpoint of both legal authority and technical capability. First, the membership of the AP is still limited. In order for APs to be fully applied, member States should conclude safeguards agreement with the IAEA. As of January 2009, only about 89 countries have APs in force as shown in Figure 6.4. In particular, some countries with significant nuclear activities such as Iran are not participating in the AP. Second, Nuclear Supplier Group (NSG)'s Dual-Use Items (DUIs) are not included in AP requirements, whereas Zangger Committee (ZC)'s Especially Designed or Prepared (EDPs) are currently listed in Annex II of the AP.[257] The collection of information about Dual-Use Items (DUIs) will be one of the important parts in strengthening IAEA safeguards. But the volume of legitimate trade, especially in sensitive DUIs is a bit overwhelming and

[257] Carlson and Leslie, "Safeguards Intensity as a Function of Safeguards Status".. The IAEA needs to review, update, and expand the control list contained in Annex II to the Additional Protocol.

would tend to swamp the IAEA's analysts.[258] Third, in practice, IAEA inspectors are not given unlimited access to nuclear facilities. States can still designate restricted areas, and access to those restricted areas requires advance notice. A member state can use so-called "***managed access***" with a view to preventing the dissemination of proliferation sensitive information.[259]

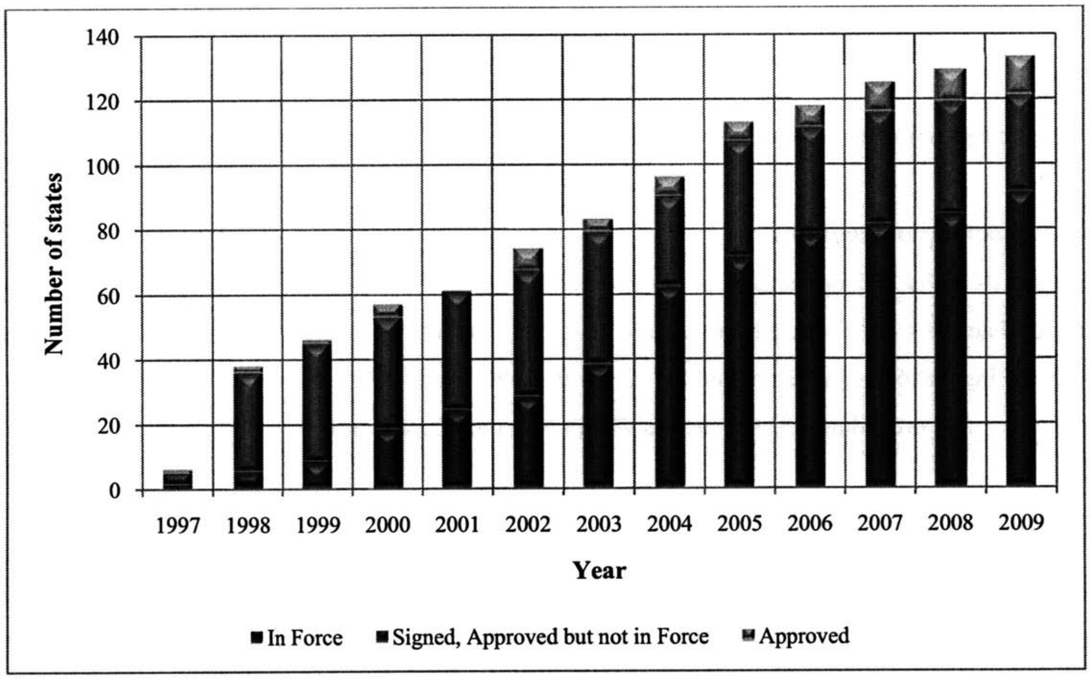

Figure 6.4 Number States with Additional Protocols[260]

6.5.4. Integrated Safeguards

Since the early 1990s, the Agency has been developing "*Integrated Safeguards*,"[261] to maximize effectiveness and efficiency within available resources through an optimized combination of all safeguards measures available to the Agency under comprehensive safeguards agreements and additional protocols. This type of safeguards can be a partial solution to resolving the issues of resource shortage in the IAEA and to reducing burdens of states from the IAEA's inspection activities,

The IAEA must be able to draw two conclusions in order for a state to qualify for the implementation of integrated safeguards: non-diversion of declared nuclear material; and the absence of undeclared nuclear material and activities in the states as a whole. These conclusions should be re-affirmed annually. If the Agency were not able to re-affirm, then corrective actions would be taken.

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[258] Personal communication with John Carlson and Russell Leslie, Jan.8, 2009.

[259] Article 7 of INFCIRC/540 provides the situations where managed access can be applied.

[260] Annette Berriman, Russell Leslie, and John Carlson, "Information Analysis for IAEA Safeguards" (paper presented at the INMM 2004 Symposium, Orlando, FL, July 2004).

[261] Jill N. Cooley, "Integrated Nuclear Safeguards: Genesis and Evolution," in *Verification Yearbook 2003*, ed. Trevor Findlay (London, United Kingdom: VERTIC, 2003).

6.6 Overall Schematic of IAEA Safeguards Inspections

IAEA verification systems can be classified into three categories; verification of reported information by states, verification of absence of non-reported activities or compliance with IAEA safeguards by inspection system on site, and verification via monitoring. All information gathered through verification activities is compiled, analyzed, and documented in Safeguards Implementation Reports (SIRs). According to the type of safeguards applied, different inspection regimes and subsequently, different detection technologies are applied. In this section, different types of inspection regimes are reviewed. Different technologies used for verification activities will be reviewed in Chapter 7.

6.6.1. Inspection Regimes

Safeguards visits and inspections are performed by IAEA inspectors at nuclear facilities or Locations outside Facilities (LOF) based on the safeguards agreement concluded by the IAEA and a state. Four types of inspections can be applied as shown in Table 6.4. Each type has a different scope, purpose, frequency, and procedures. These factors will impact the effectiveness of an IAEA inspection.

Table 6.4 Different Types of IAEA's Inspections and Visits under CSA[262]

Types	Purpose	Circumstance	Para
Ad hoc inspections	•Verification of a State's initial report of nuclear material or reports on changes •Verification of the nuclear material involved in international transfers	•Before a subsidiary arrangement has entered into force	71
Routine inspections	• Regular inspections for verification of nuclear material accountancy	•Defined schedule	72
Special inspections [263]	•Resolution of inconsistent information obtained between from routine inspections and declared by states •Access to information or locations in addition to ad hoc and routine inspections	•If the IAEA estimates that information made available by the State concerned is not adequate for the IAEA to fulfill its responsibilities under CSA.	73 [a]
Safeguards visits	•Design Information Verification •Fact finding and technical discussions in connection with the development of safeguards approaches •Negotiations and discussions with facility and State authorities regarding safeguards implementation matters.	•At appropriate times during the lifecycle	46-48

Note: [a] Also Paragraphs 53 and 53 of INFCIRC/66.

[262] IAEA, *IAEA Safeguards Overview: Comprehensive Safeguards Agreements and Additional Protocols* ([cited May 5 2009]); available from http://www.iaea.org/Publications/Factsheets/English/sg_overview.html..

[263] The Director General is empowered to request a special inspection in a CSA state, based upon unresolved questions that suggest that a state may be in violation of its CSA provisions. The provisions of the AP for complementary access are intended to improve the ability to resolve significant questions in the light of experience.

6.6.2 Randomized Regimes

To increase the efficiency of safeguards through increasing proliferators' unpredictability, the IAEA developed randomized inspection regimes. Randomized inspection regimes can be categorized depending on three factors: the nature of the timing of the inspection, the notice given to the facility, and whether they can occur during off-hours. Current inspection regimes that are available to the IAEA are shown in Table 6.5:

Table 6.5 IAEA's Randomized Inspections [IAEA Glossary (2001) and Sanborn (2004)] [264]

Category	Description	Reference
Random inspections	An inspection performed at a facility or a location outside facilities on a date chosen randomly	IAEA Glossary
Unannounced inspections	•An inspection performed at a facility or a location outside facilities for which no advance notice is provided by the IAEA to the State before the arrival of IAEA inspectors. •These inspections involve very short notice with several hours and can occur at any time including off-hours.	Para 84 of 153 Para 50 of 66
Short notice inspections	•An inspection performed at a facility or a location outside facilities for which less advance notice is provided by the IAEA to the State than provided than paragraph 83 of 153.	Para 72 of 153
Short Notice Random Inspection (SNRI)	•An inspection performed both on short notice and randomly (on a date chosen randomly). •Part of a safeguards approach developed for LEU fuel fabrication plants subject to safeguards, in order to provide improved coverage of domestic transfers of nuclear material. •SNRIs may be used at other facilities as necessary, including GCEPs.	IAEA Glossary
Limited Frequency Unannounced Access (LFUA)	•Part of safeguards approach developed for GCEPs subject to CSA at a stated uranium enrichment level of five percent or less.	Hexapartite Safeguards Project (HSP)

6.7 State Reporting Systems

6.7.1 State System of Accounting for and Control of Nuclear Material (SSAC)

Each State with a CSA is required to establish and maintain a State System of Accounting for and Control of Nuclear Material (SSAC). The SSAC is the state authority which is on, office or persons who are formally designated to keep track of nuclear material and activities and to interact with national or international entities such as the IAEA on safeguards implementation measures. An effective SSAC will require legislation and regulations as well as staff trained on the reporting procedure as shown in

[264] IAEA, *IAEA Safeguards Glossary 2001 Edition, International Nuclear Verification Series No.3* (Vienna, Austria: IAEA, 2002)., pp.84-89. For more discussions see Jonathan Sanborn, "Considerations Regarding the Scheduling and Implementation of Random and Unannounced Inspections, IAEA-SM-367/12/04," (2004)..

Figure 6.5. The practice of Nuclear Material Accountancy (NMA) begins with facility operators at the facility level and finishes with the SSAC at the state level.

An effective SSAC contributes to the deterrence and detection of theft or misuse of nuclear material, thereby contributing to the security of nuclear material and combating illicit trafficking. Through the ***IAEA SSAC Advisory Service (ISSAS)***, its legislative and technical assistance programs, the IAEA helps states develop the laws and regulations, providing recommendations and suggestions for improvements to their State systems for accountancy and control (SSACs) of nuclear material.[265]

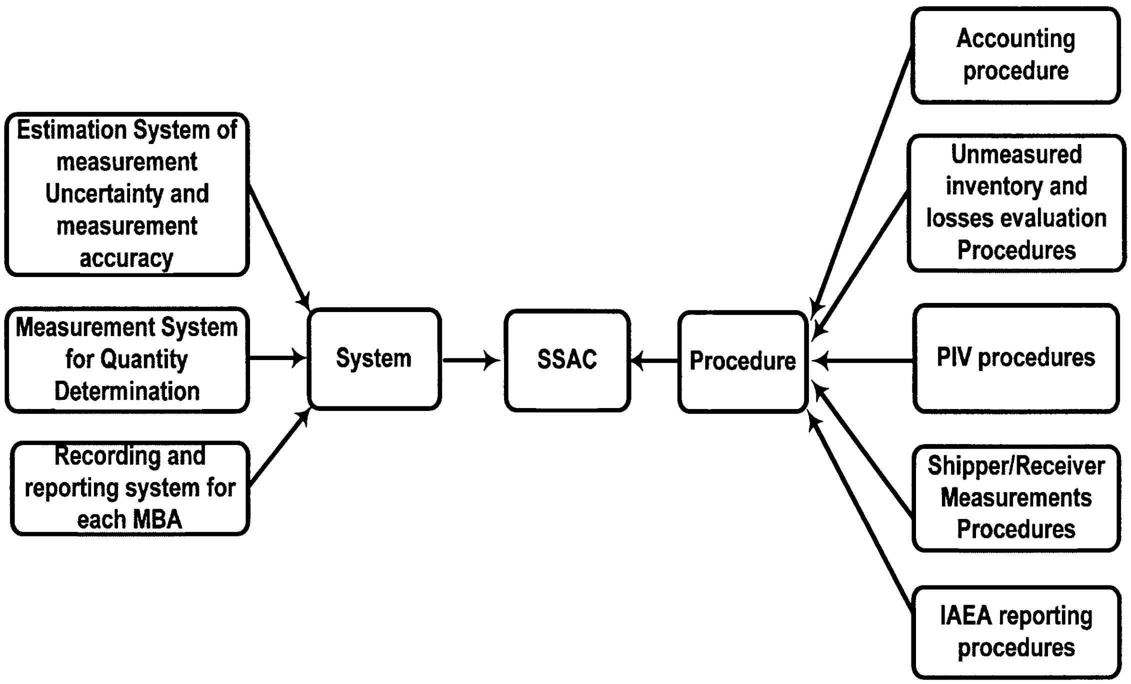

Figure 6.5 Components of SSAC

6.7.2 Voluntary Reporting Scheme (VRS)

Voluntary Reporting Scheme (VRS) was introduced in 1993 for the voluntary reporting by States of nuclear material not otherwise required to be reported to the IAEA under CSA, and of exports and imports of specified equipment and specified non-nuclear material. VRS was later incorporated in Annex II of INFCIRC/540 with a list of specified equipment and non-nuclear material. Under the AP, states are required to provide information on uranium mining, nuclear fuel cycle-related research and development, and the production and transfer of specified items. However, VRS cannot be forced in states where the AP is not in force, and non-compliance with the VRS is not the violation of IAEA safeguards.

265 IAEA, "Non-Proliferation of Nuclear Weapons & Nuclear Security, Overview of Safeguards Requirements for States with Limited Nuclear Material and Activities," (Jun. 2006)..

6.7.3. Physical Inventory Verification (PIV)

A. Undertakings of States

Facility operators are supposed to report physical inventories[266] at least once a year to the IAEA. Since October 1991 all inventory changes must be reported monthly within 30 days after occurrence as Inventory Change Reports (ICRs). The physical inventory declared by the facility operator is verified by the IAEA through a Physical Inventory Verification (PIV) inspection. During the period, IAEA inspectors verify randomly- selected items on the inventory list for existence and consistency with item descriptions.[267]

B. Undertakings of the IAEA

The IAEA can establish an itemized list of each facility's nuclear material inventory on the basis of the data contained in the initial report and subsequent inventory changes. Verification of such itemized lists can be carried out during the first few months of the implementation of the comprehensive safeguards agreement. PIV is conducted on a yearly basis by the IAEA to verify the amount of physical inventories and physical inventory changes (including the analysis of shipper-receiver differences and Material Unaccounted For (MUF) over successive material balance periods). Between PIVs, monthly inspection activities can take place, and these are called Interim Inventory Verifications (IIVs).

After completion of verification activities, two types of final reports are submitted to the IAEA:

- Physical Inventory Listing (PIL): a summary of the facility's inventory
- Material Balance Report (MBR): a summary of all the changes in inventory during the past Material Balance Period (MBP)

The IAEA can compare data declared by states and data obtained through PIV activities. When these two reports are consistent, the MBP for the each facility is closed for the past year.

C. Limitations

First, physical inventory reports are still subject to falsification by states because nuclear material inventory is reported to the IAEA monthly. Second, NMA involves statistical errors. Even though International Target Values (ITVs) were suggested, MUF would be large enough to divert sufficient nuclear materials for a weapon if the state in question has significant legitimate nuclear activities.

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[266] Physical inventory is the sum of all the measured or derived estimates of batch quantities of nuclear material on hand at a given time within a material balance area, obtained in accordance with specified procedures. INFCIRC/153, para.113. Records and reports systems are stated in paragraphs 51-58 and 59-65, respectively.

[267] Oleg Bukharin, "U.S.-Russian Bilateral Transparency Regime to Verify Nonproduction of HEU," *Science & Global Security* 10 (2002)., Appendix C. IAEA Safeguards at Enrichment Plants.

6.7.4. Design Information Verification (DIV)

A. Undertakings of the IAEA

Design Information Verification (DIV) is the process to verify declared design information on the construction of new nuclear facilities, and it is central to the implementation of IAEA safeguards especially at nuclear facilities that deal with fissile materials such as uranium enrichment facilities (UEFs) and plutonium reprocessing facilities (PRFs).

The IAEA has the right to verify the design information throughout the lifetime of a facility from construction to decommissioning up to once a year. The DIV is performed through inspector observation, appropriate measurements and tests in order to confirm (i) that the actual facility is constructed in line with the design information submitted by the states, (ii) the initial inventory of nuclear materials, and (iii) that the facility operates in the same way as explained by the state.[268]

As for UEFs, the DIV provides a reference for understanding the normal steps for introducing feed and removing product and tails, and for assuring thereafter that no temporary or permanent modifications are made that would allow the plant or any part of it to be used for the production of undeclared HEU.

B. Undertakings of States

The IAEA requires states to provide Design Information Questionnaires (DIQs) on new facilities as well as on changes in existing facilities that handle safeguarded nuclear material as soon as the state authorities decide to construct, authorize construction, or modify a facility. According to VRS or the AP, states are generally required to report Design Information Questionnaires (DIQs) 180 days before they begin construction of new nuclear facilities, and this information is used by the IAEA for verification.[269] DIQs will include data on material flows, safeguards arrangements, and facility layout.

C. Limitation

A certain state may have a different requirement with regard to the DIV. For example, according to safeguards agreements between Iran and the IAEA (INFCIRC/214 of 1974), Iran is required to report DIQs 60 days prior to the introduction of nuclear material into the facility. But, the IAEA requires states to provide design information 180 days before the start of construction work since the adoption of "93+2 programme."[270]

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[268] Thomas Shea, "Reconciling IAEA Safeguards Requirements in a Treaty Banning the Production of Fissile Material for Use in Nuclear Weapons or Other Nuclear Explosive Devices," *Nuclear Arms Control* Two (1999)..
[269] Bukharin, "U.S.-Russian Bilateral Transparency Regime to Verify Nonproduction of HEU.".
[270] For more information see, R.J. Budnitz et al., "Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts, NUREG/CR-6372 ".

6.8 Conclusion of Safeguards Activities

6.8.1 Information Analysis

The information of interest to the IAEA includes (i) nuclear material accountancy (the quantities of nuclear material), (ii) transfer of equipment and technology, and (iii) any activities related to nuclear fuel cycle. The IAEA gathers a full range of information through state declarations, in-field verification activities, and other sources including third parties and open sources as shown in Figure 6.6.

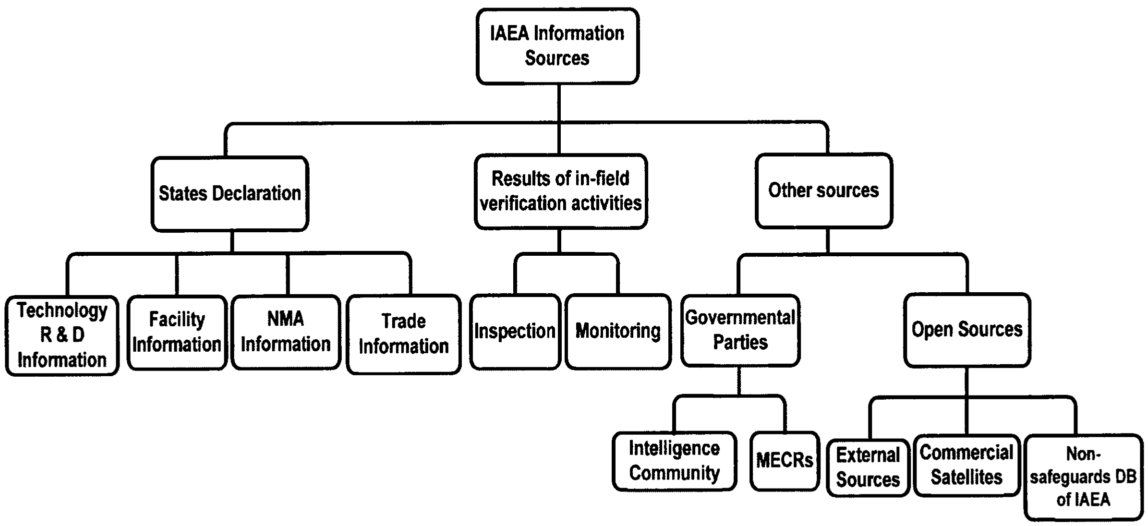

Figure 6.6 Information Sources of the IAEA[271]

Collection and evaluation of information from open sources makes an important contribution in the information analysis process. Open source information alerts the Agency to nuclear trafficking events not yet reported through official channels. For example, trade of materials for non-nuclear use that contain uranium contaminants can be identified through the evaluation of open sources. When the Secretariat obtains information from an open source, it seeks confirmation from the Member State concerned.

The IAEA analyzes all the information that they have collected from various sources to produce annual Safeguards Implementation Reports (SIRs). The accuracy, quality, and reliability of information are the main foci during the process of information analysis. However, the actual process of information analysis requires particular skills and expertise in information handling, technical knowledge about the nuclear fuel cycle, nuclear weaponization activities, and even knowledge about the States.

The Division of Information Management under the Department of Safeguards is in charge of data processing, secure information distribution, information analysis, and knowledge generation necessary to the IAEA for independent, impartial and credible safeguards conclusions. Among four

[271] "INFCIRC/640, Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report Submitted to the Director General of the IAEA.", pp. 9-10

sections within this division, the Section for Information Collection and Analysis (ICA) contributes to the analysis of all-sources of information necessary for credible conclusions, concerning the compliance of States with their safeguards obligations. The ICA participates in the information review process and deals with technologies for information collection, processing, dissemination, and analysis in support of the State evaluation process. Nuclear Trade and Technology Analysis Unit (TTA) is within this section.[272] The TTA centralizes analysis of all procurement networks.[273]

6.8.2 Modeling Efforts to Support Information Analysis

The importance of the IAEA's information analysis capabilities is significantly increasing with the expansion of the volume of information that the Agency collects. During "***Programme 93+2***", as its task five, "Improved Analysis of Information on States' Nuclear Activities," the IAEA developed a model to identify, describe, and characterize the nuclear activities of states. Features such as a state's nuclear fuel cycle technologies, all plausible state-specific acquisition paths for acquiring weapons-usable material, and the state's potential with regard to enrichment or reprocessing were modeled.[274] This model is called the "***Physical Model***". The model can be used as a tool for ensuring the coherence and consistency of the various nuclear programs and the proliferation pathways available to each state.[275]

Inputs for the Physical Model can be any type of information related to proliferation activities. Clandestine nuclear facilities tend to release unique indicators may imply that those facilities are under construction or under operation. A multiple indicators may be required in order to raise the reliability of safeguards conclusion. In this regard, the Physical Model can process multiple types of information, which is qualitative or indicative.[276] Table 6.6 shows the types of information used in the Physical Model. The Physical Model is currently under periodic review and serves as a fundamental technical component of the IAEA's state evaluations process.

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[272] Clandestine trade in sensitive nuclear technology was suddenly heightened in late 2003, subsequently Board of Governors (BOG) requested investigation why it had increased. In an effort to stop this activity, Nuclear Trade Analysis Unit (NUTRAN) was established in 2004.

[273] The TTA receives and gathers three types of information: Trade in the items listed in the Additional Protocol Annexes for those states with an AP in force; Voluntary reporting by supplier states for trade involving states without an AP; and Items and non-nuclear materials not included in the AP Annexes.

[274] Z. Liu and S. Morsy, "Development of the Physical Model, IAEA-SM-367/13/07," (2007)., <http://www-pub.iaea.org/MTCD/publications/PDF/ss-2001/PDF%20files/Session%2013/Paper%2013-07.pdf>

[275] Berriman, Leslie, and Carlson, "Information Analysis for IAEA Safeguards".; Australian Safeguards and Non-Proliferation Office (ASNO), "Annual Report 1999-2000, Annex G ASAP, Australian Safeguards Assistance Program," (2000)..

[276] Jun Liu, Da Ruan, and Roland Carchon, "Synthesis and Evaluation Analysis of the Physical Model Indicator Information by Computing with Words" (paper presented at the Proceedings of the 5th International FLINS Conference, Gent, Belgium, September 16-18 2002).. During "*Programme 93+2*", as its task five, "Improved Analysis of Information on States' Nuclear Activities," the IAEA developed a model to identify, describe, and characterize the nuclear activities of states. Features such as a state's nuclear fuel cycle technologies, all plausible state-specific acquisition paths for acquiring weapons-usable material, and the state's potential with regard to enrichment or reprocessing were modeled. This model is called the "*Physical Model*".

Table 6.6 Factors Analyzed for Use by the Physical Model [Liu and Morsy (2007)[277]]

Information types	Contents	Collection Means
Trade Activity	• Especially Designed Equipment	• MECRs, • States declaration
	• Dual-Use Items	
Technology R & D	• Equipment, instrument, operation,	• States declaration
By-products Effluents	• Environmental signatures, • Discharges, • Retained waste	• In-field verification • Commercial satellites • Intelligence community
Nuclear Material	• Feed material for nuclear facilities to produce weapons-usable materials	• States declaration • In-field verification • MECRs
Non-Nuclear Material	• Auxiliary material	
Other observables	• Auxiliary system, • Casks/containers	• In-field verification • Commercial satellites • Intelligence community

6.8.3 Safeguards Reports

After all verification activities are analyzed, the Secretariat of the IAEA reports the results and conclusions to individual states, to the IAEA Board of Governors, and to the UNSC as summarized in Table 6.7.

Table 6.7 Reporting of Safeguards Implementation by the IAEA [278]

To	Title of Report	Content
States with CSA but no AP	90 (a) statement	Statement on inspection results
	90 (b) statement	Conclusions on verification activities for each facility over a material balance period.
States with an Item-Specific Safeguards Agreement	Safeguards Transfer Agreement (STA) letter	Statement that the inspection disclosed no departure from the terms of the safeguards agreement
States with CSA and AP	10 (a) statement	Referring to the relevant article in AP
	10 (b) statement	The results of activities in respect of questions or inconsistencies
	10 (c) statement	Conclusions drawn from inspection activities
Board of Governors	Safeguards Implementation Report (SIR)	Statements on safeguards implementation in the preceding calendar year

277 Liu and Morsy, "Development of the Physical Model, IAEA-SM-367/13/07.".
278 "INFCIRC/640, Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report Submitted to the Director General of the IAEA."

A summary of the report is issued annually to highlight the main achievements and developments. These summaries are in the form of 'Safeguards Statement', and 'Backgrounds to the Safeguards Statement and Executive Summary.'[279]

6.9 Physical Protection of Nuclear Material

6.9.1 Physical Protection of Nuclear Material and Nuclear Facilities

The basic guidelines for physical protection systems were developed by the IAEA during the early 1970s. The basic concepts, purposes, and functions of physical protection are provided in INFCIRC/225/Rev.4., titled as the Physical Protection of Nuclear Material and Nuclear Facilities.[280] This requires that appropriate measures, consistent with national requirements, should be taken to protect the confidentiality of information relating to transport operations, including detailed information on the schedule and route. This sets an objective for States to (1) establish conditions which would minimize the possibilities for unauthorized removal of nuclear material or for sabotage and (2) to provide information and technical assistance in support of rapid and comprehensive measures for location and recovery of missing nuclear material and minimization of the radiological consequences of sabotage.

Physical protection generally consists of a variety of measures for the protection of nuclear material or facilities against sabotage, theft, and diversion. Physical protection measures can be divided into administrative and technical measures. The States should have legislation to provide the regulation of physical protection. In addition, the State should define requirements for the physical protection of (i) nuclear material and (ii) nuclear facilities. As for nuclear material, the document requires physical protection against unauthorized removal of nuclear material in use and storage; and nuclear material during transport, depending on the nuclear material categorization (Category I, II and III according to total amount, radiation exposure, and enrichment ratio). As for nuclear facilities, this document requires different physical protection requirements against sabotage of nuclear power reactors and other facilities.

6.9.2. Convention on the Physical Protection of Nuclear Material (CPPNM)

A. CPPNM of 1980

The original CPPNM was opened for signature in March 1980 with entry into force February 1987. The Convention was focused primarily on nuclear material being shipped internationally. The Convention

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[279] IAEA, *Reports & Reviews* ([cited Oct. 10 2008]); available from http://www.iaea.org/Publications/Reports/index.html.

[280] The guidance given in INFCIRC/225 recognizes that the implementation of these requirements will vary from country to country depending on their existing constitutional, legal and administrative systems; the assessment of the threat for the potential theft of nuclear material or sabotage of nuclear facilities; the technical skills and the professional and financial resources available to the competent authority; and social customs and cultural traditions.

set international standards for nuclear trade and commerce and established a framework for international cooperation in the field of physical protection.

The Convention required state parties to ensure they have the necessary instruments in place to implement the Convention. The Convention obliges state parties to ensure the protection of nuclear material within their territory or on board their ships or aircraft during international nuclear transport. The obligations described in the document are as follows:

•Make specific arrangements and meet defined standards of physical protection for international shipments of nuclear material,

•Cooperate in the recovery and protection of stolen nuclear material,

•Make as criminal offences specified acts to misuse or threats to misuse nuclear materials to harm the public, and

•Prosecute or extradite those accused of committing such acts.

B. Amended CPPNM

By the late 1990s many states not were parties to the CPPNM believed its scope, which was limited to nuclear material in international transport, was too narrow. In 1999, the IAEA convened an open-ended group of experts to consider whether there was a need to amend the CPPNM. In 2001, the group of experts recommended that the CPPNM should be amended and proposed a set of physical protection objectives and fundamental principles. The IAEA Board of Governors adopted those recommendations, and the IAEA convened a group of legal and technical experts to draft an amendment to the CPPNM. In July 2005, amendment that significantly broadened and strengthened the Convention, so-called "the Amended CPPNM," was adopted by consensus.[281]

The Amended CPPNM outlines security requirements for the protection of nuclear materials against terrorism and provides for the prosecution and punishment of offenders of international nuclear trade laws.[282] The amended CPPNM makes it legally binding for States Parties to protect nuclear facilities and material in peaceful domestic use and storage as well as in transport. It also provides for expanded cooperation between and among States regarding rapid measures to locate and recover stolen or smuggled nuclear material, mitigate any radiological consequences of sabotage, and prevent and combat related offenses. The amendments will take effect once they have been ratified by two-thirds of

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[281] IAEA, "Amendment to the Convention on the Physical Protection of Nuclear Material (INFCIRC/274/Rev.1)," (May 1980)..

[282] Squassoni, Bowman, and Behrens, "CRS Report for Congress: Proliferation Control Regimes: Background and Status.".

the States Parties of the Convention.[283] As of January 2009, the CPPNM has 139 parties with 45 signatories.[284]

6.9.3. International Physical Protection Advisory Service (IPPAS)

The IAEA International Physical Protection Advisory Service (IPPAS) was developed to provide advice to member states to assist them in strengthening the effectiveness of their national physical protection system, according to the Convention on the Physical Protection of Nuclear Material (INFCIRC/274/Rev.1). The implementation of CPPNM requirements will vary in different states from many aspects. Thus, a case-by-case approach should be applied. The IPPAS is available to all countries with nuclear materials and facilities.

On receipt of a request for an IPPAS mission, the IAEA will designate a Technical Officer and compose a team of experts in physical protection. The Service proceeds from a document review, interviews with personnel, and direct observation. The team will compare the procedures and practices of physical protection in a member state with (i) the obligations specified under the CPPNM (INFCIRC/274/Rev.1), (ii) the Physical Protection of Nuclear Material and Nuclear Facilities (INFCIRC/225), and (iii) equivalent good practices elsewhere. The team will make an IPPAS mission report that contains recommendations and suggestions. However, it should be noted that the ultimate responsibility for physical protection is that of the Member State.[285]

6.9.4. Illicit Trafficking Database (ITDB)

The ITDB has been released annually since 1995 in response to nuclear black market activities. As of August, 2007, ninety six states are the members of the ITDB program. The ITDB was designed to facilitate exchange of authoritative information on incidents of illicit trafficking and other related unauthorized activities involving nuclear and other radioactive materials among states. Over the years its purpose has expanded to maintaining and analyzing this information with a view to identifying common trends and patterns.

The information for ITDB is based on state-confirmed information about illicit trafficking as well as open sources. The ITDB Secretariat produces Quarterly and Annual Reports containing statistics of the ITDB information and its assessment. According to these reports, incidents of nuclear trafficking have increased over the last several years. It is not clear whether this increase in trafficking reflects

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[283] IAEA, *International Conventions & Agreements: Convention on the Physical Protection of Nuclear Material* ([cited Apr. 4 2008]); available from http://www.iaea.org/Publications/Documents/Conventions/cppnm.html.; Andrew Leask, "Global Initiative to Combat Nuclear Terrorism: Implementing the Amended Convention on the Physical Protection of Nuclear Material," in *Regional Seminar* (Sydney, Australia: 2007)..

[284] IAEA, *Status of Convention on the Physical Protection of Nuclear Material* (Sep. 24, 2009 [cited Oct. 31 2009])..

[285] IAEA, *Guidelines for IAEA International Physical Protection Advisory Service (IPPAS)* ([cited Feb. 5 2009]); available from http://www.iaea.org/OurWork/SS/Protection/foreword.html.

what really happens because this increase might be partially revealing of better reporting from states-parties.

6.10 Challenges of IAEA Safeguards

Despite continued significant efforts to increase the efficiency and effectiveness of IAEA safeguards, the IAEA is still facing a lot of challenges as listed in Table 6.8. Challenges are described in terms of capabilities and resources.

Table 6.8 Summary of Challenges

Classification	Challenges
Legal capabilities	• Under the CSA, inspectors' access is limited to declared facilities. Even at declared facilities, restricted areas can be set. • A state can block or hinder effective implementation of technical measures.
Compliance-enforcing resources	• The IAEA does not have legal authority to enforce compliance with obligations when a suspected compliance is detected.
Verification resources	• The IAEA does not conduct routine verification measures at uranium mines and concentration plants. [a] •The IAEA lacks technological capabilities for detecting some level of defects and verifying nuclear facilities. • The development of facility-specific safeguards is not satisfactory yet. • The IAEA does not have resources to manage a large volume of information concerning nuclear trade. • The IAEA lacks financial resources because of a zero real-growth budget on the IAEA for about 20 years prior to 2004. [b]
Implementation resources	• The Additional Protocol (AP) is not universally applied. • Most IAEA programs are limited in membership -The Amended Convention on the Physical Protection of Nuclear Material (CPPNM) -Illicit Trafficking Database (ITDB)

Notes
[a] Under AP, uranium mines and concentration plants are subject to safeguards verification measures, although the IAEA does not required detailed NMA. The IAEA can verify these facilities using complementary access.
[b] If the IAEA could have a resident inspector at the facilities, its verification resources can be significantly increased.

6.11 IAEA's Treatment of States in Non-Compliance

In the case of a state's non-compliance with safeguard arrangements, the IAEA itself does not have any significant enforcement methods. Article XII, paragraph A.7 of the IAEA Statute states that the IAEA has the right "*to suspend or terminate assistance and withdraw any material and equipment made available by the Agency….*," in the event of non-compliance. However, it is highly unlikely that the IAEA could exercise this right, especially if proliferators had acquired nuclear elements through black markets. In such a case, the IAEA would need to refer the case to the United Nations Security Council. In order to refer a case of non-compliance, the IAEA would need to provide the international community with the expected non-proliferation assurances for the state, i.e., through special inspections or complementary access. Currently, narrow legal interpretation of the IAEA's authority under a CSA and AP makes it extremely difficult. Thus, the IAEA has been developing a model called "***Temporary Complementary Protocol (TCP)***" to deal with this problem as shown in Figure 6.7.

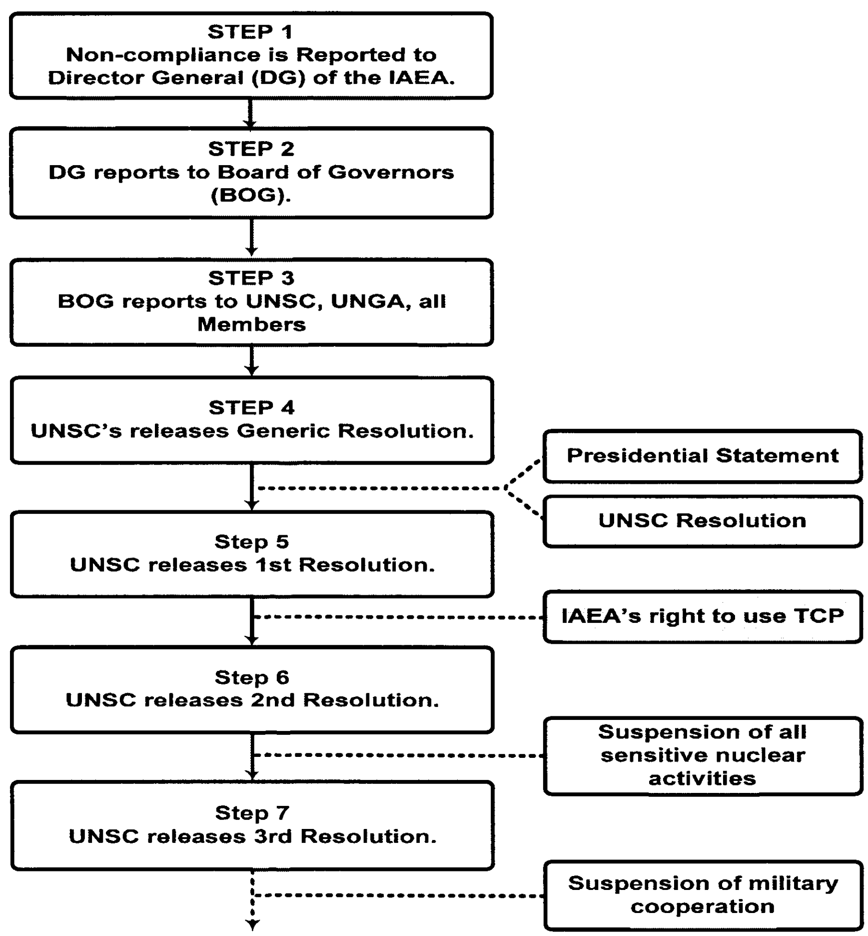

Figure 6.7 Overall Schematic in Case of Treating Non-Compliance

The TCP can make up for the weaknesses of the AP that requires correction when a state found to be attempting to evade the IAEA verification system. The TCP can address five main areas for strengthening the IAEA's authority for verification. These areas include: access to information (including clarifications and amplifications in order to resolve questions and inconsistencies; access to persons; access to locations; access to data and documents; and other types of restrictions on: freedom of movement; the use of the IAEA's equipment (including recording messages); and limitations on the number of designated inspectors, visas etc.[286]

6.12 Summary

IAEA safeguards systems and security measures including administrative issues were reviewed mainly from a legal perspective. The implementation of IAEA safeguards varies over states in consideration of the status of the states and safeguards agreements that were made between the IAEA and the states. It is not easy but critical to distinguish different features of each type of safeguards system. The IAEA is facing challenges because of the rapidly-increasing number of nuclear facilities and nuclear material transfers and subsequent lack of resources to deal with challenges. However, the IAEA is continuing its efforts to strengthen the safeguards system and to use its limited resources in an effective and efficient way, in cooperation with member states.

The greatest challenge for nuclear safeguards has been to establish an effective detection system against undeclared or clandestine nuclear activities. Many safeguards experts argue that states that intend to acquire nuclear weapons would not try to divert nuclear material from declared nuclear facilities but instead create a clandestine weapons program.[287] However, there exist proliferation pathways to acquire nuclear weapons from declared nuclear facilities by capitalizing on the loopholes of the current NPT regime or by taking the risk of being detected based on prepared scenarios.

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[286] P. Goldschmidt, " IAEA Safeguards: Dealing Preventively with Non-Compliance," (Washington, D.C: Carnegie Endowment for International Peace, 2008). Available from
< http://www.carnegieendowment.org/files/Goldschmidt_Dealing_Preventively_7-12-08.pdf>
[287] Fischer and Stein, "On-Site Inspections: Experience from Nuclear Safeguarding."

CHAPTER 7 IAEA'S TECHNOLOGICAL CAPABILITIES FOR SAFEGUARDING DELCARED NUCLEAR FACILITIES AND MATERIALS

7.1 Introduction

This chapter reviews technical capabilities of the IAEA in terms of both what technical measures it has and what technical measures can do as well. The reason of reviewing only the IAEA's technical capabilities is that the IAEA, currently, is the only component that has verification resources and technical capabilities as a regular feature in the NPT regime. The IAEA has technical tools in order to achieve its safeguards objectives stated in Chapter 6.

The IAEA's technology for safeguards includes Non-Destructive Assay (NDA), Destructive Assay (DA), Load Cell-Based Weighing System (LCBS), Containment and Surveillance (C/S), and Unattended and Remote Monitoring (UNARM). It is very important to understand the current status of technical capabilities of the IAEA for evaluating the detection probability of proliferation activities, if any. The analysis of technical capabilities is focused on the technical specification of the IAEA safeguards measures for inspection and monitoring activities with focus on uranium enrichment-related activities. The IAEA can or should borrow technical capabilities from other components of the NPT regime for detecting clandestine nuclear activities. The applicability of these capabilities for detecting clandestine nuclear facilities will be reviewed in Chapter 11.

7.2 Non-Destructive Assay (NDA)

7.2.1 Introduction to NDA Techniques

Techniques for the determination of U-235 enrichment ratio (UER) at Uranium Enrichment Facilities (UEFs) and for the assessment of plutonium-containing materials at Plutonium Reprocessing Facilities (PRFs) can be broadly categorized into two types: NDA and DA. NDA techniques include gamma-ray spectrometry (GRS), neutron spectrometry, X-ray fluorescence (XRF), K-edge densitometry,[288] Nuclear Resonance Fluorescence Imagery (NRFI),[289] and Tunable Diode Laser Spectrometry (TDLS).[290] The

[288] Densitometry measures photons that are transmitted through the sample without interaction, whereas XRF measures the radiation produced by photons that interact within the sample. As far as enrichment measurement is concerned, densitometry is usually better suited for uranium-bearing samples with high concentrations, where as XRF is the more useful technique for a sample with low concentration.

[289] William Bertozzi et al., "Nuclear resonance fluorescence and effective Z determination applied to detection and imaging of special nuclear material, explosives, toxic substances and contraband, "*Nuclear Instruments and Methods in Physics Research B*, Vol.261, (2007), pp.331-336; and William Bertozzi and Robert J. Ledoux, "Nuclear Resonance Fluorescence Imaging in Non-Intrusive Cargo Inspection," < http://www.passportsystems.com/pr/CAARI_Presentation.pdf>

[290]Natacha Peter et al., *Tunable Diode Laser Spectroscopy in International Safeguards* (2007 [cited Dec. 2008]); available from <http://tdls.conncoll.edu/2007/Peter%20TDLS%20in%20International%20Safeguards_Paper%20(2).pdf>.;A.G.B

technique of choice depends on what kind of energy is efficiently working in the measurement. GRS and neutron spectrometry could be further classified as passive or active, depending on whether a detector senses spontaneous decay or induces the radiation from a material using an external source.[291]

Among these techniques, GRS is the most widely used technique for UER measurement. GRS detectors can be divided into high-Purity germanium (HPGe) semiconductor, CdZnTe semiconductor, and NaI scintillator. Each detector has different performance features that determine resolution capabilities, efficiencies, and requirements for measurement.[292]

NDA offers great advantages over DA in terms of timeliness, low costs, ease of operation and maintenance, and operator safety. NDA measurement can be made during an inspection without sampling as well as without altering the physical or chemical state of the nuclear material. Neutron spectrometry is not as efficient as GRS in UER measurement. In neutron measurements, the sample's matrix and physical dimensions strongly influence the extent of neutron interactions between the sample and the detector. A passive neutron measurement is not appropriate for UER estimation because of low neutron emission from non-irradiated uranium material. Also, it should be noted that NDA is more or less inferior to DA in terms of accuracy and precision.[293]

7.2.2 Uranium Enrichment Measurement with NDA

NDA can be applied to an entire fuel-cycle for material accountancy, process control, and perimeter monitoring to meet the demands of the IAEA's safeguards inspection activities. NDA can provide useful information such as UER, the total uranium content, and so forth; among these, UER is the most important information.[294] IAEA inspectors can select the appropriate UER measurement technique under specific measurement conditions such as the physical form of uranium (solid, liquid, or gas), matrix of uranium, properties of uranium containers, and even different presumed UERs.

A variety of direct or indirect ways of measuring UER have been developed using different daughter nuclides of U-238 and U-235 and different energy ranges of interests in relation to the gamma-ray line separation capability of detectors. Nuclear reaction equations for U-235 and U-238 are given as follows:

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erezin et al., "UF6 Enrichment Measurements Using TDLS Techniques," *Spectrochim Acta A Mol Biomol Spectrosc* 66, no. 4-5 (2007).

[291] For more information see R. N. Ceo and K. A. Thomson, "Some NDA Techniques Applied to International Safeguards Projects," *Journal of Radioanalytical and Nuclear Chemistry* 243, no. 1 (2000).

[292] For comparison of these detectors, see Duc T. Vo, "Comparison of Portable Detectors for Uranium Enrichment Measurements," *Journal of Radiological and Nuclear Chemistry* 276, no. 3 (2008)., pp.693-698; and Rolf Arlt, Victor Ivanov, and Kevin Parnham, "Advantages and Use of Cdznte Detectors in Safeguards Measurements."

[293] IAEA, "Non-Destructive Assay (NDA): Instruments and Techniques for Agency Safeguards," *IAEA Bulletin* 19, no. 5 (Oct. 1977)..

[294] For more information on quantitative analysis see N.C. Tam et al., "Non-Destructive Analysis of Low-Enriched and Natural U Samples by Gamma-Spectrometry," *Nuclear Instruments and Methods in Physics Research A* 515, no. 2003 (Dec. 2007)., pp.644-650. The "m" stands for metastable and indicates a nucleus with additional energy.

$$ {}^{238}_{92}U \xrightarrow{\alpha} {}^{234}_{90}Th \xrightarrow{\beta-} {}^{234m}_{91}Pa \xrightarrow{\beta-(99.85\%)} {}^{234}_{92}\mathrm{U} $$

$$ {}^{234m}_{91}Pa \xrightarrow{0.15\%} {}^{234}_{91}\mathrm{Pa}+\gamma \qquad (7.1) $$

$$ {}^{235}_{92}U \xrightarrow{\alpha} {}^{231}_{90}Th \qquad (7.2) $$

Two methods are available in measuring UER; the infinite thickness method (or enrichment meter principle coupled with attenuation correction) and the intrinsic calibration method using peak-ratio techniques. The infinite thickness method uses ***enrichment meter principle*** uses a standard uranium calibration set with attenuation correction. This technique uses the fact that the net peak area under the 185.7 keV γ-ray is directly proportional to the UER when the infinite thickness condition is fulfilled. However, this method has two main drawbacks. First, this method requires the calibration of detectors using two reference nuclear material standards with different enrichments prior to measurement of unknown samples.[295] Thus, the use of this technique is limited to calibrated geometries.[296] Second, for gaseous UF6 at pressures on the order of ten torr, the mean-free path is on the order to 50 meter. Thus, the enrichment-meter principle cannot be applied. [297] The ***intrinsic calibration method*** measures the ratios of known peak intensities by applying a relative efficiency curve as a function of energy. Several gamma intensities from individual uranium isotopes are measured and then these values are normalized to a common efficiency curve.[298]

7.2.3 Gas-Phase Enrichment Measurements Using High Resolution Gamma-ray Spectrometry

Either Am-241 or Co-57 can be used as a calibration source as well as XRF-inducing source for a High Purity Germanium (HPGe) detector, depending on the pressure. First, at high pressure (around 700 torr), Am-241 is used as a source and the UER of UF6 is calculated from:

$$ E = \frac{R}{C\, ln(T_{Am-241})} \qquad (7.3) $$

[295]Haluk Yücel, "The Applicability of MGA Method for Depleted and Natural Uranium Isotopic Analysis in the Presence of Actinides (232Th, 237Np, 233Pa and 241Am)," *Applied Radiation and Isotopes* 65 (2007).

[296] N.C. Tam et al., "Non-Destructive Analysis of Low-Enriched and Natural U Samples by Gamma-Spectrometry." The application of infinite thickness method is limited to about 0.25 cm for metal samples and 7cm for UF6 with a density of 1 g/cm3.

[297] for the enrichment-meter principle to be valid, the unraium material thickness must be equivalent to several mean-free path s for the 185.7-keV gamma ray from U-235.

[298] N.C. Tam et al., "Non-Destructive Analysis of Low-Enriched and Natural U Samples by Gamma-Spectrometry."

where C is a calibration constant, R is the measured count rate of the 186-keV gamma rays from the decay of U-235, and T_{Am-241} is the transmission through UF6 gas of 60-keV gamma rays from an external Am-241 source. [299] This technique is intended for use at the Portsmouth GCEP as a technique to measure the enrichment in the product UF6 gas entering the product withdrawal facility. These measurement results were intended to serve as a partial-defect check for material-balance verification.

Second, at low pressure (i.e., inside cascade halls of GCEPs), the 122–keV of Co-57 source is used instead because the density of UF6 does not allow for sufficient sensitivity for the transmission measurement. The uranium $K_{\alpha 1}$ 98.4-keV x-ray count rate measures the total amount of uranium in the gas. The $K_{\alpha 1}$ is induced by X-Ray Fluorescence (XRF) of the gaseous UF6 using a Co-57 source. [300] [See Appendix D]

7.2.4 NDA Application at UEFs: CHEM and CEMO

Cascade Header Enrichment Monitor (CHEM) and Continuous Enrichment Monitoring System (CEMO) are two types of on-line NDA measurement techniques authorized by the IAEA.

A. Cascade Header Enrichment Monitor

LANL developed CHEM during the mid-1980s as a method of detecting the presence of HEU in cascade header piping and providing a Yes/No answer. It has the advantage that it can take into account the presence of deposits on the piping wall, and thus provide an enrichment measurement for the gas only. It was intended for use during LFUA inspections to the cascade hall. Since the measurement uses a HPGe detector, which has a relatively low gamma-ray detection efficiency, the technique takes a fairly long time to reach a result. The technique worked well on the large diameter cascade header pipes at the Portsmouth GCEP. However, it turned out that the URENCO plant piping was much smaller in diameter and operated at somewhat lower pressures than at Portsmouth GCEP. As a result, it was much more difficult to obtain a usable result.

The CHEM was used during the HEU Downblending Verification Experiment at the Portsmouth Gaseous Diffusion Plant (PGDP) in 1997-1998 in order to explore the applicability of

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[299] Hastings A. Smith Jr., "Chapter 7. The Measurement of Uranium Enrichment Measurement," in *Passive Nondestructive Assay of Nuclear Materials* (U.S. Government Printing Office, 1991).

[300] 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, NM: Los Alamos National Laboratory, March 1999).; For further details, see Stephane F. Terracol et al., "Ultra-High Resolution Gamma-Ray Spectrometer Development for Nuclear Attribution and Non-Proliferation Applications" (paper presented at the 2004 IEEE Nuclear Science Symposium Conference Record, Rome Italy, Oct. 16-22 2004).; and D.A. Close et al., "The Measurement of Uranium Enrichment for Gaseous Uranium at Low Pressure" (paper presented at the Proceedings of the 7th Annual Symposium on Safeguards and Nuclear Material Management, ESARDA, Leige, Belgium, May 21-23 1985)..

CHEM as a system for rapid on-line NDA measurements of gaseous UF_6 enrichment.[301] However, the HPGe detector, which must be cooled to liquid-nitrogen temperatures, was in very close contact with diffusion-plant process piping, which operates at fairly high temperatures; as a result, the detector failed on several occasions due to heating of the detector cryostat, with consequent degradation of its energy resolution. This problem would not occur at many GCEPs, since the piping at these plants operates at ambient, or near ambient, temperatures. These detectors are not universally used in all Gas Centrifuge Enrichment Plants (GCEPs). The IAEA is currently upgrading CHEM using extensive Monte Carlo simulations.[302] The enrichment ratio is determined from the measured gamma spectrum using corresponding gamma and X rays from the decay of both U-235 and U-238 isotopes. The CHEM must perform energy calibration on the equipment using XRF to get full E peak efficiency prior to measurement.[303]

B. Continuous Enrichment Monitoring System

CEMO was developed in the past by the UK Support Programme, and it is applied at only two URENCO GCEPs in the Western Europe. This equipment monitors the UER of gaseous UF_6 in the product pipe as it is being produced, and it sends daily information to EURATOM (Luxembourg) and IAEA HQs to confirm its working status and the non-presence of HEU at the facility.[304] The CEMO is nonintrusive, and provide timely, continuous detection of HEU production and monitoring of enrichment in a manner that is acceptable to the operator. Currently, CEMO is not operating on a continuous basis. However, it would be a highly desirable surveillance technique that could be applied inside the cascade area not only to detect changes in piping or operation characteristics but also to measure inventory (hold-up) in the cascades.

The CEMO requires two parameters for UF6 enrichment calculation: the total mass of U-235 and the pressure of the process gas. The total mass of U-235 in the pipe is monitored by measuring the 185.7 keV gamma rays emitted by that isotope. The process gas pressure (P) is determined from the measurement of the absorption of Ag Ka x-rays (22.25 keV) emitted by a Cd-109 source. These two measurements permit the enrichment (E) to be calculated from:[305]

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[301] P. L. Kerr et al., "IAEA Verification Experiment at the Portsmouth Gaseous Diffusion Plant: Report on the Cascade Header Enrichment Monitor, LA-13557-MS."; David Gordon et al., "IAEA Verification Experiment at the Portsmouth Gaseous Diffusion Plant, BNL-65714," (1998).

[302] IAEA, Research and Development Programme for Nuclear Verification 2008-2009 (2009). ,p.87. Dmitry Sharikov, "Verification Challenges for Safeguarding Uranium Enrichment Plants," *ESARDA Bulletin*, no. 37 (Dec. 2007).The false alarm probability of these detectors is estimated as 0.001.

[303] D.A. Close et al, Operating Procedures for the Cascade Header Enrichment Monitor: Non-Destructive assay (DA) on 3-Inch and 8-Inch Header Pipes at the Portsmouth Gaseous Diffusion Plant, LA-UR-98-1211, Los Alamos National Laboratory. This approach is called "intrinsic calibration approach."

[304] Peter Friend, "Urenco's Views on International Safeguards Inspection" (paper presented at the 8th International Conference on Facility Operations-Safeguards Interface, Portland, OR, Mar.30-Apr.4 2008).

[305] The CEMO is not based on the enrichment-meter principle because the "infinite-thickness" criterion is not met. It may be said that the CEMO uses "pressure-corrected 186-keV count rate. Personal communication with an expert via e-mail. Dec.8, 2009.

$$E = R \times (\frac{K}{P}) \qquad (7.4)$$

where R is the measured count rate of the 186-keV rays and K is a constant, specific to each detector. Both measurements use a low-resolution NaI scintillation detector coupled to a photomultiplier, which is gain-stabilized using the 88-keV gamma-rays from the same source. Comparisons of these two techniques are shown in Table 7.1.

Table 7.1 Comparison between CEMO and CHEM [306]

Specification	Cascade Header Enrichment Monitor (CHEM)	Continuous Enrichment Monitoring System (CEMO)
Developer	Los Alamos National Laboratory	United Kingdom
Portability	Portable [a]	Permanently installed
Purpose	Inspections	Monitoring and inspections
Technique	High Resolution Gamma Spectrometry	Low Resolution Gamma Spectrometry
Application	Portsmouth Gaseous Diffusion Plant (1997 and 1998)	GCEP at Carpenhurst, U.K. and the Dutch Almelo facilities since the 1990s.
Calibration requirement	Relative efficiency calibration [307]	Geometry-dependent calibration constants
Calibration source [308]	Co57 (272 days of a half-life) or Am-241 (also serves as (XRF source)	Cd-109 (453 days of a half-life) for normalization [b]
Limitation	Energy resolution might be affected by vibration and temperature, and geometry.	X-ray absorption varies with pipe diameter, wall material , temperature and cascade pressures

Notes

[a] Some hardware (such as "mounting fixtures, collimators, and x-ray fluorescence source) remains in place and is located within tamper-indicating enclosure seals by the IAEA.

[b] The IAEA sees it as non-sustainable due to its usage of a short-lived source (Cd-109) and limitation in monitoring each cascade in a commercial size GCEP: the IAEA considers replacement of Cd-109 with I-129 which has half-life of 1.57×10^7 years. This is for pressure correction purposes.

7.2.5 Limitations of Gamma Ray Spectrometry (GRS)

For Gamma Ray Spectrometry (GRS), the accuracy of measurement results can be influenced by systemic uncertainties[309] as well as statistical uncertainties. Causes of systematic uncertainty include

[306] Sharikov, "Verification Challenges for Safeguarding Uranium Enrichment Plants."

[307] D.A. Close et al., "Operating Procedures for Cascade Header Enrichment Monitor: Non-Destructive Assay (NDA) on 3-Inch (7.62 Cm) and 8-Inch (20.32 Cm) Header Pipes at the Portsmouth Gaseous Diffusion Plant," (Los Alamos National Laboratory, 1998).;D.A. Close et al., "LA-UR-98-1211.". N.C. et al. Tam, "Non-Destructive Analysis of Low-Enriched and Natural U Samples by Gamma-Spectrometry," *Nuclear Instruments and Methods in Physics Research A* 515, no. 3 (Dec. 2003).

[308] For comparison of x-ray spectrums of uranium from Co57 and Cd109 see Fig.10.3 and 10.4, p.317 in M. C. Miller, "Chapter 10 X-Ray Fluorescence," in *Passive Nondestructive Assay of Nuclear Materials, NUREG/CR-5550*, ed. Doug Riley et al. (U.S.Government Printing Office, Mar. 1991).

attenuation factors with regard to the thickness and composition of container walls,[310] interfering radiations from deposits in the inner wall of the containers and from neighboring storage containers, the chemical or physical states of uranium-containing material,[311] the UER of material, and the calibration procedure.

• Thickness of container

As the thickness of a UF_6 container increases, so does attenuation of gamma rays. For example, a 16 mm wall of a UF_6 cylinder attenuates the 90 to 100 keV radiations by about a factor of 250.[312] This can be overcome by establishing so-called "attenuation correction," the relationship between the relative fluctuation of the enrichment result and the relative fluctuation of the wall thickness.

•Influence of UER

The accuracy of UER measurements is degraded in case of very low U-235 enrichment ratios.[313]

•Deposits of material on the cylinder walls

If uranium or thorium daughter products are deposited on the cylinder walls, UER accuracy may be compromised. This can be overcome through ***Nuclear Forensics***, using Th231 and Th 234, which are the daughter products of U-235 and U-238, respectively. Two principal gamma ray double peaks (or doublet) of Th-234 (92.38 and 92.80 keV, and 62.86 and 63.29 keV)[314] will be prominent compared to the singlet from Th-231 (84.2 keV) as time goes on. This occurs because Th-234 has a longer half-life, 24.1 days, than that of Th-231, which is 25.52 hours.[315]

•Material of cylinders

In the case of the Russian gas centrifuge technology, the detectability using CEMO or CHEM is significantly reduced because it uses steel piping.[316]

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[309] S. Guardini et al., "Performance Values for Non Destructive Assay (NDA) Techniques Applied to Safeguards: The 2002 Evaluation by the ESARDA NDA Working Group," (ESARDA, 2003).; and Stephane F. Terracol et al., "Ultra-High Resolution Gamma-Ray Spectrometer Development for Nuclear Attribution and Non-Proliferation Applications".

[310] Hastings A. Smith Jr., "Chapter 7. The Measurement of Uranium Enrichment Measurement.", p.209.

[311] See Table I for measures results in different forms of matrices in R. Gunnik et al., "Mgau: A New Analysis Code for Measuring U-235 Enrichments in Arbitrary Samples, UCRL-JC-114713" (paper presented at the The IAEA Symposium on International Safeguards,, Vienna, Austria, Mar. 8-14 1994).

[312] R. Gunnik et al., (1994). If the HRGS is used, then the gamma-ray response is corrected for cylinder-wall thickness as measured by an Ultrasonic Thickness Gauge (ULTG).

[313] In general, one can measure the UER of HEU quite well with gamma-ray NDA because of the high count rate of 185.7 keV gamma rays and the low background underneath the 185.7 keV peak.

[314] James Kaste, Benjamin Bostick, and Arjun Heimsath, "Determining 234^{Th} and 238U in rocks, soils, and sediments via the doublet gamma at 92.5 keV," *Analyst*, Vol.131, (2006), pp.757-763.

[315] I. Adsley et al., Decay of Th-234 and Daughter Pa-234m in Secular Equilibrium: Resolution of Observed Anomalies, DoE Report No: DOE/CPR2/41/1/219, (June 1996). <http://resource.npl.co.uk/docs/science_technology/ionising%20radiation/clubs_groups/nsuf/2005/cpr2_41c.pdf>

[316] A. Panasyuk, A. Vlasov, S. Koshelev, T. Shea, D. Perricos, D. Yang and S. Chen, "Tripartite Enrichment Project: Safeguards at Enrichment Plants Equipped with Russian Centrifuges," IAEA-SM-367/8/02, (2002)

7.3 Destructive Assay (DA)

Destructive Assay (DA) or High Precision Trace Analysis (HPTA) is used for material-balance verification and analysis on environmental samples. Destructive Assay (DA) provides more accurate information than NDA. DA for material-balance verification purposes has been performed for decades since the 1970s, whereas DA of environmental samples was introduced into IAEA safeguards 1996. The IAEA's Class-100 Clean Laboratory for Safeguards, a part of SAL, began operation in early 1996 and mainly provides DA for samples.[317] Techniques of DA are alpha spectrometry, mass spectrometry, isotope dilution mass spectrometry (IDMS), isotope assay, thermal ionization mass spectrometry (TIMS), and secondary ion mass spectrometry (SIMS). Mass spectrometry is the most commonly used DA technique in nuclear safeguards. [318] Table 7.2 shows the differences in applying DA techniques for material-balance verification and for environmental samples.

Table 7.2 Use of DA for Two Different Purposes

	Material balance	**Environmental samples**
Objective	Determine element and isotopic abundances in order to verify that nuclear materials are properly accounted for and that detection of the diversion of a significant quantity of nuclear material can be achieved with a high probability.[319]	Determine elemental and isotopic composition in order to verify whether or not an enrichment plant produces HEU.
Sample mass	A few grams (bulk samples)	Individual micro-sized particles collected through cotton sampling media
Techniques	Standard chemical and mass-spectroscopic techniques such as the Davies-Gray potentiometric titration method	Mass-spectroscopic techniques such as SIMS and Fission-Track TIMS

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[317] The Safeguards Analytical Laboratory (SAL) at Seiberdorf has been in existence since 1976. The SAL serves as a focal point for a Network Analytical Laboratories (NWAL) in several member states. The functions of SAL includes: provision and certification of environmental sampling kits; screening and distribution of environmental samples to NWAL coming from safeguards inspections. SAL is capable of measuring of uranium isotopic composition in uranium-containing particles by Thermal Ionization Mass Spectrometry (TIMS) or Secondary Ion Mass Spectrometry (SIMS). D. L. Donohue, "Strengthening IAEA safeguards through environmental sampling and analysis," *Journal of Alloys and Compounds* Vol.271-273, (1998), pp.11-18.

[318] Types of mass spectrometry include accelerator mass spectrometry (AMS), inductively coupled plasma mass spectrometry (ICPMS), gas source mass spectrometry (GSMS), resonance ionization mass spectrometry (RIMS), secondary ion mass spectrometry (SIMS) and thermal ionization mass spectrometry (TIMS).

[319] IAEA R & D Program for Nuclear Verification 2008-2009, page 51. Wide-Area Environmental Sampling (WAES) is defined in Article 18.g of the AP as meaning "the collection of environmental samples (e.g., air, water, vegetation, soil) at a set of locations specified by the Agency for the purpose of assisting the Agency to draw conclusions about the absence of undeclared nuclear material or nuclear activities over a wide area." The term '***wide area***' has been used to mean the collection of environmental samples that are not targeted around a suspect facility or geographic location, but instead over regions containing much larger areas (e.g., on the order of hundreds of thousands of square km).

Limitations

DA is still limited when unexpected HEU particles are discovered in UF_6 cylinders during shipping, when there is cross-contamination, and during personnel movement between different plants.[320] For example, in the case that HEU particles are found in LEU-producing facilities formerly used for HEU production, environmental sampling may be less useful because it is challenging to determine whether the HEU particles were the remnants of former operation or signatures of current operation. Cluster analyses of particulates over time or nuclear forensics may provide a solution by analyzing differences in minor isotope ratios.[321] Nuclear forensics can provide information regarding uranium age and the origin of material.[322]

7.4. Environmental Sampling (ES)

Environmental sampling was introduced into IAEA safeguards in the mid 1990s, and it has been implemented in the Additional Protocol as complement to the existing safeguards agreement.

7.4.1 Scheme of Environmental Sampling

Samples are collected in a variety of fashion for Destructive Assay (DA). The IAEA classifies the scheme of Environmental Sampling (ES) according to where and how samples are collected as follows:

(i) Swipe sampling at strategic locations within the facility; [323]
(ii) Location-specific sampling at the specified location by the IAEA; and
(iii) Wide Area Environmental Sampling (WAES).

(ii) and (iii) are both features of the Additional Protocol, however main difference is that (ii) can collect samples at only limited locations, whereas (iii) can collect samples anywhere. In this study, sampling scheme is simply divided into environmental sampling within the facility and outside the facility as shown in Table 7.3.

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[320] W. Bush, G. af Ekenstam, J. Janov, E. Kuhn and M. Ryjinski, IAEA Experience with Environmental Sampling at Gas Centrifuge Enrichment Plants in the European Union, IAEA-SM-367/10/04, (2004).

[321] Separation Theory, U-234 is typically ignored in mathematical discussions of enrichment and uranium is considered simply as a two component system. (U-234 concentrations in natural uranium vary slightly from mine to mine and these small differences in U-234 concentration can help identify the source of illicit nuclear material. Such tracking is one example of **nuclear forensics.**)
< http://www.fas.org/programs/ssp/nukes/fuelcycle/centrifuges/separation_theory.html>

[322] In some cases, it is possible to determine the age of uranium or plutonium particles via nuclear forensics. The primary objective of nuclear forensic analysis is to determine the attributes of questioned radioactive specimens, which are conveniently divided into two key forensic areas: source and route. Thus, ***Nuclear Forensics*** enables analysis on interdicted illicit nuclear and radioactive materials for clues to the materials' origins and routes of transit. If the technique that can trace the age of HEU particles can be developed, which lies in the area of Nuclear Forensics, it would resolve the last problem.

[323] Swipe samples are collected at selected areas of safeguarded facilities with squares of cotton cloth. The cotton cloth is sealed in plastic bags. It has a size of 10x10 cm and is prepared under ultra clean conditions.

Table 7.3 Different Definitions of Environmental Sampling Scheme

IAEA	Kalinowski et al. (2006)	This study	Safeguards
Swipe sampling	Swipe sampling	Sampling within the facility	INFCIRC/153
Location specific sampling	Short range (1km) and long range scheme (1-100km) from the facility	Sampling outside the facility or Environmental Sampling at Wide Area (ESWA)	INFCIRC/540 Additional Protocol
WAES			

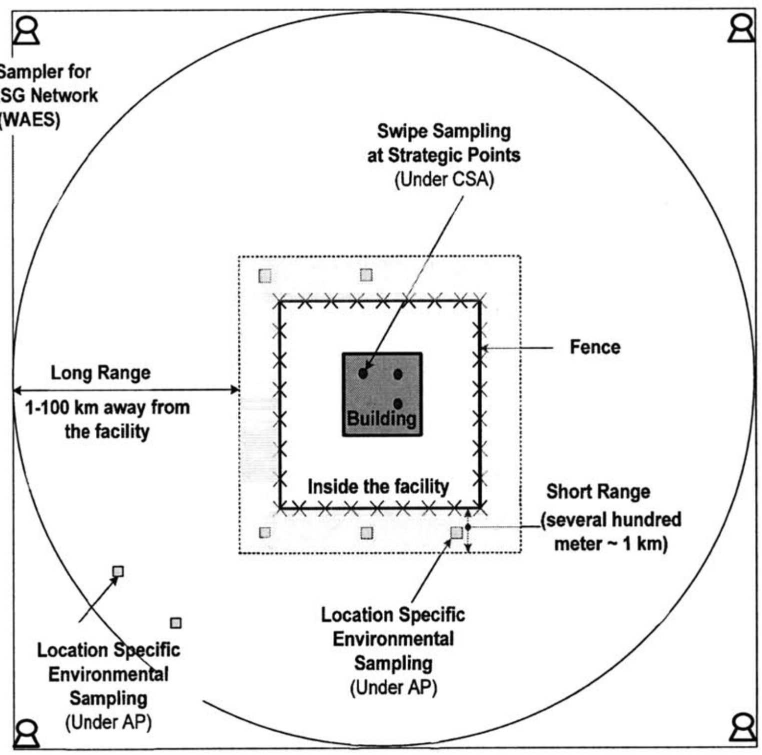

Figure 7.1 Schemes of Environmental Sampling

In 1997 and 1998, the IAEA convened a technical committee to study the technical possibilities of WAES under the Additional Protocol (AP). The evaluation of WAES implementation in the context of the Additional Protocol was completed through a Multi-Member States Support Program (MSSP) study in 1999. The study evaluated the potential feasibility of WAES for use in the detection of undeclared nuclear facilities. The conclusion was that WAES was not economically feasible because sufficiently dense network of monitoring stations must be established in order to detect weak signatures.[324] The grid constant, (the distance between samplers in a square grid) is the major factor affecting detection capability. At the time, only Wide Area Air Sampling Grid (WAASG) was

[324] In this case, an aerosol-WAES method should utilize a large number of samplers located in an area of hundreds of square kilometers for the localization of the source. The subsequent challenge is the enormous cost of installing this network system and changing filters.

considered as WAES. Even though economic justification is ignored, a detection probability is not still high enough, whereas a false-negative is high, even in a dense network.[325]

The high cost with regard to the use of WAES can be reduced in three ways: the development of screening process;[326] the use of global transport models;[327] and minimization of maintenance cost for a network stations.[328] An effort to use WAES was restored through the IAEA's Novel Technologies Program in 2004. In 2004 and 2005, the IAEA hosted a workshop and a couple of technical meetings with regard to detection of uranium enrichment using WAES.[329] However, WAES is still far from being a common feature of IAEA safeguards. Figure 7.1 shows possible schemes of environmental sampling.

7.4.2. Environmental Sampling over Wide Area (ESWA)

ESWA requires a sample collection system and a sample analysis system as shown in Figure 7.2.

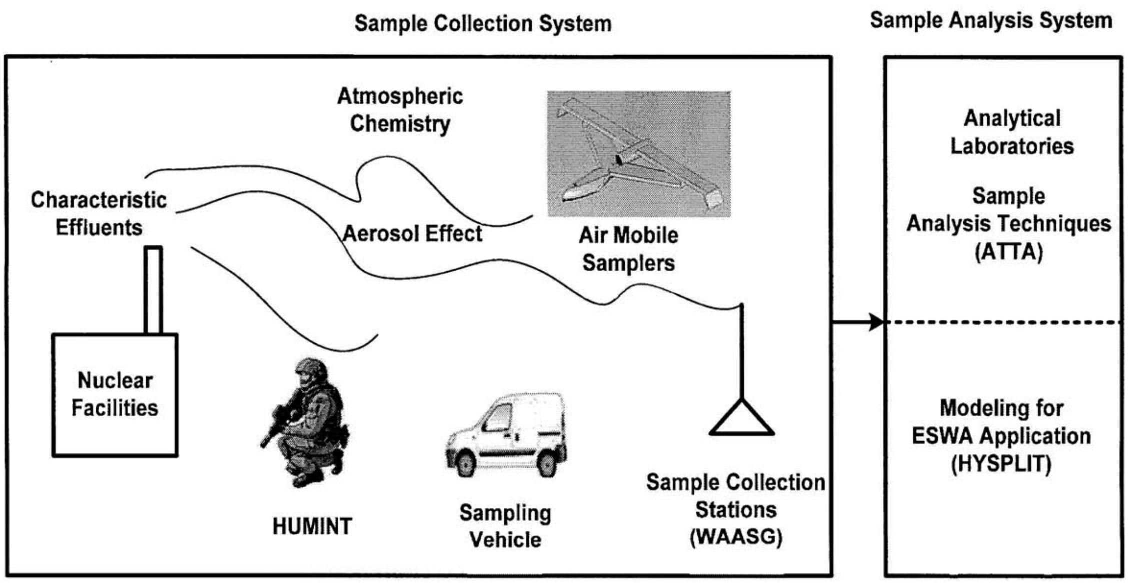

Figure 7.2 Schematic Figure of Environmental Sampling over Wide Area (ESWA)

[325] For the relationship between grid constants and probabilities of detection, see Ephraim Asculai, *Verification Revisited: The Nuclear Case*, ISIS Reports, Washington, DC: Institute for Science and International Security Press,2002), pp.101-112. Appendix 1. The Efficacy of Effluent Detection By Wide-Area Environmental Sampling.

[326] D.W. Swindle, R.L. Pearson, N.A. Wogman and P.W. Krey, "Screening of potential sites for undeclared nuclear facilities in environmental monitoring for nuclear proliferation, "*The Journal of Radioanalytical and Nuclear Chemistry*, Vol. 248, no.3 (June, 2001), pp. 599-604.

[327] Atmospheric Transport Simulations (ATS) or Atmospheric Transport Modeling (ATM) can be used to determine both optimum localization for sources and procedures for detecting clandestine proliferation activities. For information on global transport models for verification purposes, see Martin Kalinowski et al., "Atmospheric Krypton-85 Transport Modeling for Verification Purposes," *INESAP Information Bulletin*, no.27, (December, 2006), pp.17-19.

[328] Valmari T. et al., "*Aerosol Sampling Methods for Wide Area Environmental Sampling (WAES)*," Finnish support to IAEA, STUK-YTO-TR183. (June 2002).

[329] Martin B. Kalinowski, "Nuclear Safeguards and Proliferation: Remote Environmental Sampling for the Detection of Clandestine Nuclear Weapons Production and Testing," ESARDA Training Course, Ispra, (14-18 April 2008)

A. Sample Collection System

The collection system can be classified in terms of the distance from the source, the mobility of collection means, and the altitude of sampling locations (ground or air). But, ground and air sampling seem to be the best classification in many ways. Ground sampling can be called Surface Deposition Sampling (SDS)[330] and it can be performed through either mobile sampling vehicles (during on-site inspections) or Human Intelligence (HUMINT).[331] On the contrary, air sampling is done through WAASG and aircrafts. Air sampling is considered the most prominent among various means to collect samples because fine aerosol particles (diameter smaller than one micrometer) can be carried in air thousands of kilometers (km) from the source. However, HUMINT and UAVs are military intelligence assets that may be politically sensitive due to the presence of a foreign entity. In order to improve the efficiency of air sampling, optimization of sampler deployment, capabilities of filters,[332] features of particles to collect, and the intensity of source need to be considered. In addition, atmospheric chemistry and aerosol effects influence sample collection efficiency.

B. Modeling for ESWA Application

Modeling for ESWA can be used for several purposes including: estimating ESWA capability in terms of detection range for a given sample analysis capability and concentration of particles from the source or vice versa; optimized or strategic placement of sampling stations;[333] and confirming the particles selected emanated from the suspicious facility. For example, it is always desirable to locate samplers in proximity to the source for effective detection because the concentration of the non-natural nuclides decreases as the distance from the source increases. However, this is not always the case and this limitation can be overcome by simulating the transport of aerosol particles in consideration of geographical features and atmospheric environment. The transport code of NOAA's Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) is one of models that can be used for ESWA

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[330] Ephraim Asculai, *Verification Revisited: The Nuclear Case* (Institute for Science and International Security Press, 2002). Surface Deposition Sampling (SDS) that simply takes samples on the surface.

[331] The mobile samplers have three advantages over the fixed samplers: shorter detection period; elimination of the high cost for fixed monitoring sites; and increase in unpredictability. For more information see M. Kalinowski, H. Daerr, and M. Kohler, "Measurements of Krypton-85 to Detect Clandestine Plutonium Production," *INESAP Information Bulletin*, no. 27 (Dec. 2006).

[332] For more information, see T. Valmari et al., "Aerosol Sampling Methods for Wide Area Environmental Sampling (WAES): Finnish Support to IAEA," (2002).

[333] The optimization issues arise with regard to the efficiency and effectiveness of WAES: the siting process of a suspicious undeclared nuclear facility; and the optimization of sample collection means. As for sample collection stations for WAES, places where air movement converges downwind of an interested region are considered as the most efficient siting. D. W. Swindle Jr et al., "Screening of Potential Sites for Undeclared Nuclear Facilities in Environmental Monitoring for Nuclear Proliferation," *Journal of Radioanalytical and Nuclear Chemistry* 248, no. 3 (2001).

simulation.[334] The HYSPLIT simulates the transport of aerosol particles so that modelers can see how far aerosol particles can move and how fast they are diluted as they transport.

C. Sample Analysis Techniques

The capability of ESWA differs for a specific type of particles because different types of facilities emit different effluents and in different concentrations. The capability of ESWA is described in terms of a minimum detectable number density or a minimum detectable mixing ratio (or concentration) such as ppmV (parts per million by volume) or ppbV (parts per billion by volume).[335] Kemp and Glaser (2008) provided the capability of ESWA as detection range for a specific type of particle.[336] Among various analysis techniques applicable to ESWA, Atom Trap Trace Analysis (ATTA) seems to be the most prominent technique.[337] Atom Trap Trace Analysis (ATTA) is based on the laser manipulation technique of neutral atoms, and it would vastly reduce the cost of ESWA. ATTA has application in the analysis of several fission isotopes including krypton 85, strontium 90, cesium 135 and cesium 137. ATTA is also capable of analyzing two trace-isotopes of krypton, Kr-85 and Kr-81 at the parts-per-trillion level.[338]

7.4.3 Limitation in Environmental Sampling over Wide Area (ESWA)

The current level of sampling under the AP can be described as "swipe sampling away from strategic points." That is, the application of environmental sampling is still restricted to the locations that are routinely visited by inspectors.[339] The application of ESWA can be allowed only under the Additional Protocol. Even under the Additional Protocol (AP). IAEA inspectors' access to obtain environmental samples is still limited in the sense that an unlimited range of sampling is not allowed. This is because Article 9 of the AP requires prior consultations with the state to be inspected and the approval of the

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[334] R. Scott Kemp and A. Glaser, *The Gas Centrifuge and the Nonproliferation of Nuclear Weapons* (Program on Science and Global Security, Princeton University, 2007 [cited May 5 2008]); available from <http://www.princeton.edu/~aglaser/2007aglaser_splg.pdf>.HYSPLIT model simulates the transport of aerosol particles from a reference facility and provides airborne-concentration isopleths in terms of $\mu g(UO_2F_2)/m^3$. For more additional information, see M. Kalinowski, "Detection of Clandestine Production of Nuclear-Weapons-Usable Materials," *iGSE Bulletin* 2 (Dec. 2006).: 17-20.

[335] Jens Bösenberg and Martin Kalinowski, "Detecting Atmospheric UF6 and HF as Indicators for Uranium Enrichment," *INESAP Information Bulletin*, no. 28 (April 2008). It should be noted that different values would be obtained for different particles with the same technology. These values are estimated using the differential absorption cross section of the gas and the range interval where the gas is present, and the differential optical depth. DIAL is applicable to only gaseous compounds.

[336] Kemp and Glaser, *The Gas Centrifuge and the Nonproliferation of Nuclear Weapons*.

[337] iGSE, "iGSE-Detection of Clandestine Production of Nuclear-Weapons-Usable Material," *INESAP Information Bulletin*, no. 27 (Dec. 2006).. The analysis was first developed by the Argonne National Laboratory and the Independent Group of Scientific Experts_(iGSE) in 1999 with the purpose of using it on ground water and ice core dating studies.

[338] Zheng-Tian Lu et al., "Atom Trap Trace Analysis," (Argonne National Laboratory, ANL/PHY/CP-101981, 2000).

[339] Personal Communication with John Carlson, the Head of Australia Safeguards Nonproliferation Office (ASNO), in January 2009.

Board of Governors (BOG) with a view to constraining the implementation of WAES. This is due to the cost limitations and political sensitivity.

7.5. Containment and Surveillance (C/S)

Containment and surveillance (C/S) systems have been the principal means for ensuring the completeness and maintaining Continuity-of-Knowledge (CoK) of nuclear materials and safeguards equipment during the absence of inspectors between inspections since 1970s. Containment system includes tamper indicating systems and systems that maintain physical integrity of fuel or of an area where the fresh fuel casks, storage tanks are situated. Video surveillance provides a means by which access to nuclear material can be monitored and any undeclared movement of material detected. In almost all cases, containment and surveillance systems are used in combination. C/S systems have evolved from commercially available cap-and-wire seals and film cameras to modern integrated systems that can be combined with digital image surveillance and electronic sealing. C/S system can be further equipped with unattended monitoring systems or remote data transmission to provide information on a real-time basis. In this regard, C/S systems can be regarded as a part of an unattended and remote monitoring system (UNARM).

7.5.1 Containment Systems: Seals

A seal is a Tamper-Indicating Device (TID) that prevents undetected access. Seals can save inspectors' effort by eliminating the need for re-measurement of verified items or samples. However, a seal is not designed to prevent access but only in non-erasable and unambiguous way record that such access has occurred. The seals can be characterized by their main properties: single or multiple use and single or multiple on-site verification. Table 7.4 lists types of seals that the IAEA uses or develops. Electronic seals are the most sophisticated ones and permit multiple use and multiple verification purposes.

Table 7.4 Types of Seals

Types	Description	Remarks
Metal seals (CAPS)	For single use and single verification Standard IAEA E-type and X-type metal seal and seal wire	In use
Adhesive seals (VOID)	For single use and single verification VOID (Improved Adhesive Seal) and ADPS is a paper seal that is used by IAEA safeguards staff for temporary sealing of equipment and enclosures, developed to replace existing paper seals to improve detection of tampering. [340]	In use

(Continued)

[340] IAEA, New Safeguards Equipment Systems: Teaming IAEA Inspectors with Technology, 2002.

Fiber optic seals	For single use and multiple verification Cobra and In-situ Readable Ultrasonic Seal System (IRUSS)	In use
Electronic seals	Variable Coding Sealing System (VACOSS)-S is in use by the IAEA and an in situ readable electronic seal, being used with fiber optic cable.	In use
	The Electronic Optical Sealing System (EOSS) is a re-usable mechanical locking seal for long-term surveillance, which communicates via RF with a seal reader. The system employs an active fiber optic light source and light sensor to record any open/close events.	In use German Support Program[341]
	Integrable Reusable Electronic Seal (IRES) enables independent verification by different inspectorates (IAEA, Euratom, and National Inspectorate). The seal can be remotely interrogated by radio frequency and can be used with fiber optic cable or an electrical wire. [342]	The French Support Program for the IAEA Safeguards)
	TRFS (Two-way Radio-Frequency Seal)[343]	The Sandia National Lab.
Ultrasonic seals	For the monitoring, identification and verification of containers used for under-water storage of fissile materials to be reprocessed, nuclear transportation casks, or for other movable structures of strategic value [344]	Future

7.5.2. Surveillance Systems

Surveillance instruments and devices are designed to detect or confirm all movements of nuclear material and spent fuel containers. They also are used to indicate whether the integrity of the containment of nuclear material (i.e., as containers, storages, and reactor vessels, etc.,) has been maintained. Each of the video cameras, along with additional electronics for data storage and data authentication, is contained within its own tamper-indicating enclosure sealed by the IAEA. The cameras are connected by cable to an IAEA computer contained within a tamper-indicating enclosure sealed by the IAEA.

Surveillance instruments offer the possibility of increasing inspection efficiency and of reducing the inspection effort because they can operate unattended for long periods of time. All-in-one System (ALIS), All-in-one Portable System (ALIP), Digital Single Camera Optical Surveillance System (DSOS), Server Digital Image Surveillance System (SDIS), Digital Multi-camera Optical Surveillance System (DMOS), Hawk Digital Imaging System (HDIS), and General Advanced Review Station Software (GARS) are used.

[341] In November 2005, the IAEA approved the EOSS seal "for routine use" (category A). In 2006, the IAEA began to procure it for replacement of the VACOSS seal

[342] B. AUTRUSSON et al., The IRES Electronic Seals, IAEA-SM-367/14/01/P

[343] Matter, John and Tzolov, Roumen, "The T-1 Two-way Radio-Frequency Seal (TRFS) And Its Application for Joint Operator-IAEA Use, IAEA-SM-367/7/01 P.

[344] ESARDA, "JRC Ultrasonic seals," *ESARDA Bulletin*, no. 37, (December 2007), pp.66-68.

7.5.3 Application at UEFs

At Uranium Enrichment Facilities (UEFs), the most important safeguards feature is to maintain CoK about the flow of UF_6. Surveillance cameras at feed/withdrawal stations can detect the diversion of UF_6 flow at uranium enrichment plants. However, it should be noted that the use of cameras at UEFs is often limited to restricted areas because of the issue of information protection from inspectors.

The surveillance cameras are triggered to record images in any of three ways: (i) the detection of motion based on the detection of scene changes within the field of view; (ii) rapid changes in the weight observed by any other weighing systems; and (iii) elapsed-time interval. In addition, the IAEA can use surveillance cameras at the onset of the unannounced inspections. Possible locations of C/S system installations include feed, product, and tail cylinders; the uranium feed point and the product and tails removal points; and process piping, boundary valves, flanges, and locations where monitoring instruments are installed.

7.6 Load Cell Based Weighing System (LCBS)

There are two types of UF_6 –weight measuring equipment; LCBS and LCBWS as shown in Table 7.5. LCBS and LSBWS were developed by the Brookhaven National Laboratory (BNL) in 1980 and 1984, respectively. The LCBWS is designed to provide verification of UF_6 cylinder masses by the IAEA at UEFs that handle large-capacity UF_6 cylinders. LCBS can be applied at feed, product, and tails stations to measure the weights of UF_6 cylinders.

Table 7.5 Features of LCBS

Type	Year developed	UF_6 cylinders	LCBS capacity	Developer
LCBS	1980	2.277 ton	4.54 metric-ton	BNL
LCBWS	1984	9.07 and 12.70 metric-ton UF_6 cylinders	18.14 metric-ton-capacity	BNL and Oak Ridge Gaseous Diffusion Plant

The main components of a LCBWS includes a crane hook, universal flexures, load cells, eye nuts, threaded connecting rods, lifting shackles, a lifting fixture etc. The LCBWS offers the advantages of portability, ease of assembly and use, and high accuracy within ±1 kg.[345] The error of a load cell is on the order of 0.01% and it is defined as the root mean square sum of nonlinearity, hysteresis, and

[345] Wanzie McAuley, et al., "A 20-ton-capacity Load-Cell-Based Weighing System for UF6 Cylinder Mass Verifications," DE87 002803, CONF-850210-5, Jan. 1985.

repeatability.[346] The LCBWS would permit the IAEA to correlate real-time weight data, obtained as the UF6 cylinders are emptied and filled, with the "Mailbox" declarations and video-surveillance system results.

When total amounts of UF_6 are reported, care should be taken to note whether the quantities are measured in terms of uranium mass or UF_6 mass. The mass of uranium hexafluoride (UF_6) is equal to 1 uranium atom and 6 fluoride atoms. The molecular weight is therefore given by:

$$m(U) + 6m(F) = 238 + 6(19) = 352[g/mol] \qquad (7.5)$$

This makes the mass of uranium approximately **67.6** percent of that of uranium hexafluoride. [347] The IAEA reports usually describe material feed rates in terms of UF_6. However, flow rates should be converted to uranium when calculating separative properties such as the separative power. [348]

7.7 Unattended and Remote Monitoring System (UNARM)

UNARM is a term for the combined Unattended[349] Monitoring System (UMS) and Remote Monitoring System (RMS). RMS is an unattended instrument that can automatically upload data directly to IAEA Headquarters. UNARM is different from the C/S system in that UNARM is designed to report to the IAEA on a real-time basis, using satellite communication, which is assured by the Additional Protocol. UNARM will minimize intrusiveness, reduce inspection manpower requirement, and decrease exposure of personnel to radiation. With UNARM installed, surveillance data can be reviewed by safeguards at any time and thus inspections can be more effective during inspection preparation for planning and during on-site inspections. Fewer follow-up visits by inspectors will make less impact on operator's tasks performance.

For UEFs, the currently-used unattended and remote monitoring system by the IAEA is done through a continuous enrichment monitoring system (CEMO). Two UANRM instruments were used to support the Russia/US HEU purchase agreement. Los Alamos National Laboratory (LANL) developed an Enrichment Monitor (EM) based on thallium-activated sodium iodide [NaI (TI)] gamma-ray scintillation detectors for on-line measurement at Russia's uranium downblending facility. Oak Ridge National Laboratory (ORNL) also developed a Fissile Mass Flow Monitoring System (FMFM), which used a modulated neutron source to simulate fissions and NaI detectors to measure the decay product

[346] Cooley, J.N. and Huxford, T.J., "*Load-Cell-Based Weighing System (LCBWS) Equipment Survey,K/ITP-112 (ISPO-271)*," United States Program for Technical Assistance to IAEA Safeguards (POTAS), Sep.1988.
[347] The mass ratio of U-238 to UF6, which can be calculated by (238/352) x100(%).
[348] Ivanka Barzashka and Ivan Oelrich, *Separation Theory* (Federation of American Scientists, [cited Jan. 11 2009]); available from http://www.fas.org/programs/ssp/nukes/fuelcycle/centrifuges/separation_theory.html.
[349] Unattended means the absence of inspectors.

pulses downstream. This was installed on each leg of the UF_6 piping, so that both the feedstock and product were continuously monitored.[350]

However, the use of UNARM remains limited except for European countries because of the cost and reliability of techniques. In 2002, the IAEA had 63 cameras and other monitoring devices connected to 27 RMS established in five countries. Five UMS in two countries providing remote 'state of health' data were used by the IAEA.[351]

7.8 Satellite Imagery

Since the discovery of Iraq's nuclear weapons program in the early 90s, the possible roles of medium-resolution commercial satellite images were explored for monitoring nuclear proliferation activities. Under the AP, high-resolution Commercial Satellite Imagery (CSI) is being utilized as a complementary source of information in the state evaluation process. Satellite Imagery Analysis Laboratory (SIAL) was established in 2000 by the IAEA to support IAEA safeguards. What makes SIAL so different and promising is the fusion of these resources with the inspectors themselves.[352]

Satellite imagery can be obtained from both National Technical Means (NTMs) of states and privately-operated satellite systems. CSI is the imagery obtained from the latter systems and is generally referred to as "unclassified imagery publicly offered for a fee on a routine basis, whether by private or public agencies."[353] Since the early 1960s, the US and the USSR/Russia have been using their satellites as NTMs to identify and monitor each other and other countries' nuclear facilities and activities. Starting in 1972, these satellites as well as other NTMs were used to verify strategic arms control agreements, including Strategic Arms Limitation Talks (SALT) I and the Anti-Ballistic Missile treaty. As for CSI, it became available with NASA's deployment of Landsat-1 in 1972 and Landsat-2 in 1975.[354] In the United States, KH-series of U.S. military reconnaissance satellite belong to the category of NTMs.

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[350] The instruments were calibrated before shipment to Russia. Taner Uckan et al., Blend Down Monitoring System Fissile Mass Flow Monitor and Its Implementation at the Siberian Chemical Enterprise, Seversk, Russia, ORNL/TM-2005/137, (Springfield, VA: ORNL, Jan. 1996)

[351] Russell Leslie, Peter Riggs and John Clarson, "The Role of Remote Monitoring under Integrated Safeguards," Annual Meeting of the Institute of Nuclear Materials Management, Orlando, FL, (23-27 June 202) and IAEA Dept. of Safeguards, *New Safeguards Equipment Systems: Teaming Inspectors with Technology*, (2002) <http://www.iaea.org/Publications/Booklets/TeamingInspectors/teaming_inspectors.pdf>

[352] For more information on task performing process, see K. Chitumbo, S. Robb, J. Bunney and G. Leve, *Satellite Imagery and the Department of Safeguards*, IAEA-SM-367/16/08, (2008).

[353] James F. Keeley and Jason K. Cameron, "Chapter Two the Need to Know: Commercial Satellite Imagery and IAEA Safeguards," in *Non-Proliferation Arms Control and Disarmament: Enhancing Existing Regimes and Exploring New Dimensions*, ed. Peter Gizewski (Toronto, ON: York University, Centre for International and Security Studies, 1998). Commercial Satellite Imagery (CSI) first became available with NASA's deployment of Landsat-1 in 1972 and Landsat-2 in 1975.

[354] Vipin Gupta, "New Satellite Images for Sale," *International Security*, Vol.20, no.1, (Summer 1995), pp. 94-125. Commercial satellite imagery generally refers to unclassified imagery publicly offered for a fee on a routine basis, whether by private or public agencies. Keeley, J. F. and Cameron J. K., "The Need to Know: Commercial Satellite Imagery and IAEA Safeguards." In Peter Gizewski (ed.), *Non-Proliferation Arms Control and*

7.8.1 Capabilities of Satellites

Satellites can provide imagery information in different types depending on what types of imaging sensors are uploaded. Imagery information is generally categorized into visible (photo-optical), infra-red (electro-optical), and radar imaging, depending on energy levels used for imaging. For safeguards application, Visible and Near-Infrared (VNIR) and Thermal Infrared (TIR) channels are of importance and their specifications are described in Table 7.6.[355] VNIR captures infrastructure signatures, whereas TIR is sensitive to thermal signatures. TIR is very useful to detect the difference between the temperature of an object of interest and its surroundings, rather than to measure absolute temperatures. The capability of satellite imagery is often described in terms of resolution.

Table 7.6 Two Types of Satellite Sensors Useful for Detecting Nuclear Facilities

Specifications	Visible and Near-Infrared (VNIR)	Thermal Infrared (TIR)
Wavelength used	about 0.4 to 1 micrometers	about 8 to 14 micrometers
Types of information	Traditional photographic image	Relative Temperature Difference (RTD)
Description of capabilities	•Spatial resolution •Panchromatic or Multispectral •Reflective sensitivity	•Spatial resolution •Panchromatic or Multispectral •Thermal Sensitivity (TS)
Advantage	Higher resolution	Taken during the night as well as the day

Notes
[a] RTD is the temperature difference between a target and the surrounding environment.
[b]Thermal Sensitivity (TS) is the minimal RTD that TIR imagery can detect and is equivalent to Noise-Equivalent temperature different (NEdT).
[c] The square of spatial resolution is called Instantaneous Field of View (IFOV). [356]

Panchromatic and multispectral images are available in both VNIR and TIR wavelengths in satellite imagery. A panchromatic image consists of only one band in the broad visual wavelength range; thus, it produces black and white images. On the contrary, a multispectral image consists of several bands of data. Each band of the image may be displayed one band at a time as a grey scale image, or in combination of three bands at a time as a color composite image. Current CSI for VNIR has obtained

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Disarmament: Enhancing Existing Regimes and Exploring New Dimensions, (Toronto, ON: York University, Centre for International and Security Studies, 1998), pp. 13-33.

[355] Image is generated in the form of radar pulses which allows imaging at any time of day or night. Long wavelengths allow penetration of cloud cover and imagery even in dusty conditions. Yet, resolution is not as good as visible or infrared images. Images can also be subject to "noise" due to "backscatter" (a form electronic static) caused by certain unfavorable conditions such as rough seas or nearby large, metallic surfaces. Radar satellites are also susceptible to active jamming. Center for Defense Information (CDI), *Terrorism Project: Military Reconnaissance Satellites (Imint)* (2001 [cited May 5 2009]); available from http://www.cdi.org/terrorism/satellites-pr.cfm.

[356] Field of View is described as milliradians by milliradians.

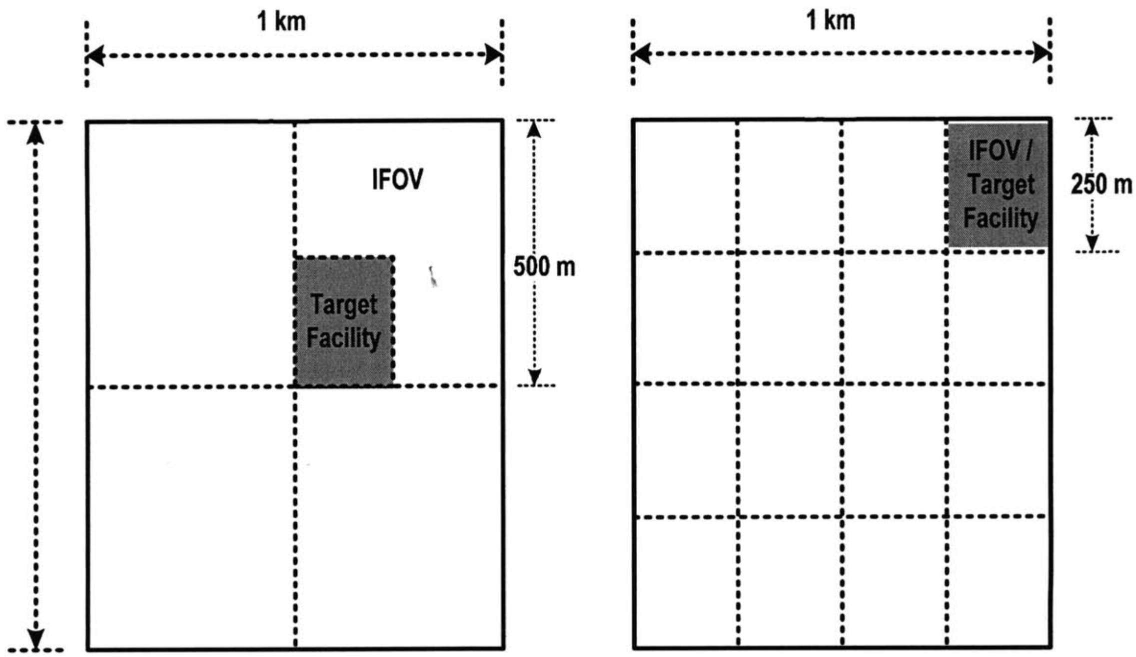
0.5 m spatial resolution and this level can distinguish the major visible characteristics of nuclear facilities.

7.8.2 Interpretation of TIR Capability

TIR imagery requires coupled analysis of spatial resolution and thermal sensitivity. For simple comparison of TIR capability the following criteria can be used:

$$\frac{Instant\ Field\ of\ View}{Field\ of\ View} \times Temperature\ Sensitivity \qquad (7.6)$$

This is further illustrated in Figure 7.3 by comparing different TIR image capabilities for detection on the same size target.



(a) 1 (km)*1 (km) FOV with 500 m Spatial Resolution (b) 1 (km)*1(km) FOV with 250 m Spatial Resolution

Figure 7.3 Description of Thermal Infrared (TIR) Imagery Capability

TIR imagery can detect a target that emits a heat when the following condition is satisfied under clear-sky conditions:

$$(Target\ Facility\ Footprint) \times (RTD) \geq (IFOV) \times (TS) \qquad (7.7)$$

Inequality (7.7) can be used in several ways. As for the detection of a clandestine GCEP, we can calculate either a minimal heat that a given GCEP should release under a given footprint of a facility or TIR's capability requirement in order to detect under a given specification of a GCEP such as a temperature release and the size of footprint. In addition, it could be said that a rough estimate about a capability of different TIR imagery can be compared using the multiplied values of IFOV and TS. Table 7.7 shows currently-available TIR capabilities.

Table 7.7 TIR Capabilities of Commercial Satellites for Land Surface Temperature

Operator	Satellite	Year Launched	TIR Resolution	VNIR Panchromatic	Thermal Sensitivity (TS)	IFOVxTS/FOV[d] (°K)
NASA	Landsat 5,7	1999	60 m	15 m	0.5-1 °K [a]	0.018-0.036
	ASTER [b]	1999	90 m	15 m	0.2 ° K	0.162
	MODIS [c]	1999	1 km	N/A	0.05 °K	50.
NOAA	AVHRR/3	1998	1.09 km	N/A	<0.1 ° K[357]	120.

Notes
[a] Thermal sensitivities of Landsat -5,7 and ASTER from Zhang (2000)
[b] ASTER from < http://www.yale.edu/ceo/Documentation/ASTER.pdf>
[c] MODIS from <http://modis.gsfc.nasa.gov/about/specifications.php>
[d] FOVs for each satellite are assumed equal as 1km for criteria (1)

7.8.3 Application of Commercial Satellite Imagery

The possible roles of CSI are as follows: (i) support for inspection planning associated with declared facilities or shut-down facilities; (ii) the provision of complementary information for detecting undeclared sites (i.e., a screening tool to detect suspicious sites); and (iii) the establishment of chronology of facilities from construction to the current operational status.[358] The effectiveness of using satellite imagery depends on knowledge about the existence of a facility and its strength level of optical and thermal signatures.[359]

7.8.4 Future Use of Satellite Imagery

The limitations of SIAL include the difficulties in identifying of small-scale undeclared facilities and the costs associated with purchasing satellite imagery. The greater access to military satellites will help to identify clandestine facilities because of their superior capabilities than commercial satellites.

[357] Personal communication with Drs. Rama Mundakkara and Xianqian Wu. For more information, see Jonathan P.D. Mittaz and Andrew R. Harris, "A Physical Method for the Calibration of the Avhrr/3 Thermal Ir Channels 1: The Prelaunch Calibration Data," *Journal of Atmospheric and Oceanic Technology* 26 (2006)., pp. 996-1019.
[358] O.J. Heinonen, *Verification of the Correctness and Completeness of Initial Declarations, IAEA-SM-367/2/02* (2002).
[359] Kalinowski, "Detection of Clandestine Production of Nuclear-Weapons-Usable Materials."

However, not all countries have access to such capabilities, and states with these satellites are not willing to share the information acquired from such satellites.[360] As far as the cost is concerned, if SIAL can purchase a percentage of satellite time under a United Nations umbrella agreement, it can save the IAEA budgets and allow the creation of effective collection strategies.

7.9 Light Detection and Ranging (LIDAR) and Differential Absorption LIDAR (DIAL)[361]

Light Detection and Ranging (LIDAR)[362] is increasingly used because of its feature that does not require sampling process. LIDAR is an active optical remote sensing technology used routinely by environmental monitoring agencies to determine the presence of pollutants in the atmosphere. LIDAR detects particles in the air by transmitting short pulses of electromagnetic radiation into the atmosphere and analyzing the backscattered light collected in a receiving telescope. A laser in LIDAR can be tuned to precise wavelengths and selectively stimulate specific molecules. In this manner, LIDAR can directly measure the properties of stimulated airborne molecules without environmental sampling. However, LIDAR is limited in specifying the chemical composition of the target particles; thus, it is used only for determining the density of unspecified particles.

Bösenberg and Kalinowski (2008) suggest that DIAL, a special application of the LIDAR technique can detect any gaseous component with high sensitivity and can determine the chemical composition of gaseous components. Yet, the current DIAL technology is limited to within the distances up to several km for the detection of clandestine GCEPs. For concentration measurement, DIAL measures two adjacent wavelengths at a peak of absorption (online) and at a trough (offline), giving a different signal. The differential nature of the measured wavelengths simplifies the measurement process. The difference between two wavelengths at different distances, a total of four signals, determines of the gas concentration.[363] In particular, DIAL has its core competence in remote sensing of trace gases that provides narrow isolated absorption lines such as UF_6 and HF. In addition, DIAL is operable from various platforms and in an automated way, if required.[364] The CALIOP LIDAR,

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360 Hui Zhang, "Strengthening IAEA Safeguards Using High-Resolution Commercial Satellite Imagery (IAEA-SM-367/16/01)" (paper presented at the Symposium on International Safeguards: Verification and Nuclear Material Security, Vienna, Austria, Oct.29 - Nov.1 2001).

361 Kalinowski, Daerr, and Kohler, "Measurements of Krypton-85 to Detect Clandestine Plutonium Production.", pp.9-12.

362 iGSE, "IGSE-Detection of Clandestine Production of Nuclear-Weapons-Usable Material." iGSE on the detection of clandestine nuclear-weapons-usable materials was launched in May 2006. The purpose of this project is three folds: develop technologies and procedures to help uncover clandestine production of weapons-usable materials; demonstrate practical usability in the field; and inform relevant political bodies as well as a wider public audience of the emergence of such new tools.

363 Spectrasyne, *What Is Dial and How Does It Work?* (2007 [cited Aug. 13 2008]); available from http://www.spectrasyne.ltd.uk/html/about_dial.html.

364 Bösenberg and Kalinowski, "Detecting Atmospheric UF6 and HF as Indicators for Uranium Enrichment.", pp.55-59.

which is one of satellite-loaded LIDARs, may show better performance than DIAL. Thus, the application of the CALIOP LIDAR is worthwhile to investigate.[365]

7.10 Design Information Verification Equipment

System for Design Information Verification (DIV) can be used to detect the presence of undeclared changes and hidden facilities that may indicate undeclared proliferation activities such as the diversion of nuclear material and provision of undeclared material. Currently, two types of DIV equipment are developed: 3D Laser Range Finder (3DLR) and Ground Penetrating Radar (GPR).

The three-dimensional Laser Range Finder (3DLR) is already being used by the IAEA for DIV activities at Rokkasho Plutonium Reprocessing Plant. This system can detect any structural changes within an accuracy of millimeters through the comparison of scanned images with the previous ones. Changes are shown in highlight such as piping arrangements.[366] However, the software of 3DLR needs further improvement including the revision of 3DLR encryption module.[367] GPR is one of geophysical non-destructive methods and it can detect hidden objects and structures within facilities during regular inspections. GPR is not in use yet; however, GPR also has the potential for DIV and for detecting undeclared facilities.[368] The current challenge of GPR is to interpret the resulting radargrams in an immediate and unequivocal fashion.[369]

7.11 Limitations and R & D Efforts

The IAEA incorporates new technologies as the techniques and implementation of safeguards continue to evolve. Novel technologies are defined as those for which the methodology has not been applied previously by the IAEA for safeguards applications. In 2004, the IAEA General Conference called upon the Secretariat to examine innovative technological solutions to strengthen the effectiveness and improve the efficiency of IAEA safeguards. The IAEA Board of Governors decided to call for help in exploring novel technologies and verification approaches to detecting clandestine activities. The IAEA started its NTP and collected technical proposals from member states. The Novel Technologies Project (The project Novel Techniques and Instruments for Detection of Undeclared Nuclear Facilities, Material and Activities) was established in 2005. Table 7.8 shows the technical limitations of current inspection techniques. Most of these novel techniques are under development through the Member State Support Programs (MSSPs).

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[365] For more information, see David M. Winker et al., "Status and Performance of the Caliop Lidar," (Hampton, VA: NASA Langley Research Center, 2004).
[366] Mark Zendel, "IAEA Safeguards Equipment," *International Journal of Nuclear Energy Science and Technology* 4, no. 1 (2008).
[367] IAEA, *Research and Development Programme for Nuclear Verification 2008-2009.*, p.48.
[368]Ibid.,p.31.
[369] Zendel, "IAEA Safeguards Equipment."

Table 7.8 Techniques for Future Development Requirement[370]

Technique	Future
Containment	•Vulnerability assessment of sealing system and Laser Surface Authentification (LSA) design[371] •Development of the ultrasonic sealing bolt, a conduit monitoring system. •Application of Radio Frequency Identification (RFID)[372]
Surveillance	•Laser Item Identification System (LIIS) Development and Field Testing for UF_6 cylinder tracking[373] • Hawk Digital Imaging System (HDIS) and 3D Spatial Imaging Techniques
Swipe sampling / Destructive Assay (DA)	•Nuclear Forensics for tracing the origin of uranium particles and determining age (age dating) of uranium and plutonium particles •Establishment of cost effectiveness network of laboratories for nuclear material analysis while optimizing NWAL resources for reduction of the time response, the shipment costs, and the waste production.
ESWA	•Laser Ablation Techniques to detect secondary environmental signatures[374] •Laser-Induced Breakdown Spectroscopy (LIBS) and Optically Simulated Luminescence in Forensics (OSL) •Air sampling field trials
Non-Destructive Assay (NDA)	•Establishment of NDA Data Acquisition Platform (UNAP) •Improvement in detection capability, efficiency and effectiveness of detectors based on Tunable Diode Laser Spectrometry (TDLS) •Improvement of CHEM and CEMO •Enhancing the capability of detecting undeclared materials and activities for illicit trafficking monitoring and support for design information verification.
Unattended and Remote Monitoring (UNARM)	•Unattended Monitoring System (UMS): Extension of currently installed UMS lifetime and standardization of UMS. •Remote Monitoring (RM): Data transmission methods, data security, data integrity check and state of health monitoring. CEMO is part of RM.
Satellite imagery	•Information establishment on characteristic imagery signatures of facilities used in various enrichment process •Information establishment on high-spatial-resolution thermal and hyperspectral data[375] •Population of a comprehensive data imagery indicators/signatures for all nuclear fuel cycle processes •The use of geospatial information combined with satellite imageries

[370] IAEA, *Research and Development Programme for Nuclear Verification 2008-2009.* This document provides introduction to the IAEA's R & D projects that are conducted through Member State Support Programmes.

[371] 3D scanning system for DIV and the IAEA is investigating the authentication of metal seals, used widely in many safeguards applications. By scanning a seal's unique microscopic surface structure, the inherent "fingerprint" produced provides increased assurance against seal-counterfeiting.

[372] Currently, UF6 cylinders can only be tracked manually using tag checks. Tags based on radio frequency identification (RFID) do not meet strict safeguards requirements concerning tamper resistance.

[373] The IAEA has successfully tested LIIS that identified individual UF6 cylinders by the intrinsic spatial irregularities that are unique to each cylinder. This technique would be coupled with video surveillance to provide fully unattended system for continuity of knowledge. M. Zendel, "IAEA Safeguards: Challenges in Detecting and Verifying Nuclear Materials and Activities."

[374] IAEA, "Internal Report on the IAEA Technical Meeting on Application of Laser Spectrometry in IAEA Safeguards (August 28 to September 1, 2006)," (Vienna: 2006).

[375] Carlson and Leslie, "Safeguards Intensity as a Function of Safeguards Status".

7.12 Schematic of IAEA's Safeguards Measures

Figure 7.4 shows IAEA's safeguards measures, both legal and technical, that are currently being used. This figure was drawn based on Comprehensive Safeguards Agreements (CSA). The newly-added features of AP are represented in shaded boxes. It should be noted that AP is not universalized in most IAEA member states. In addition, Wide Area Environmental Sampling (WAES) can be implemented once the IAEA Board of Governors (BOG) approves the use of the technique, as requested. But, it is still limited because of immature level of technology and political sensitivity.

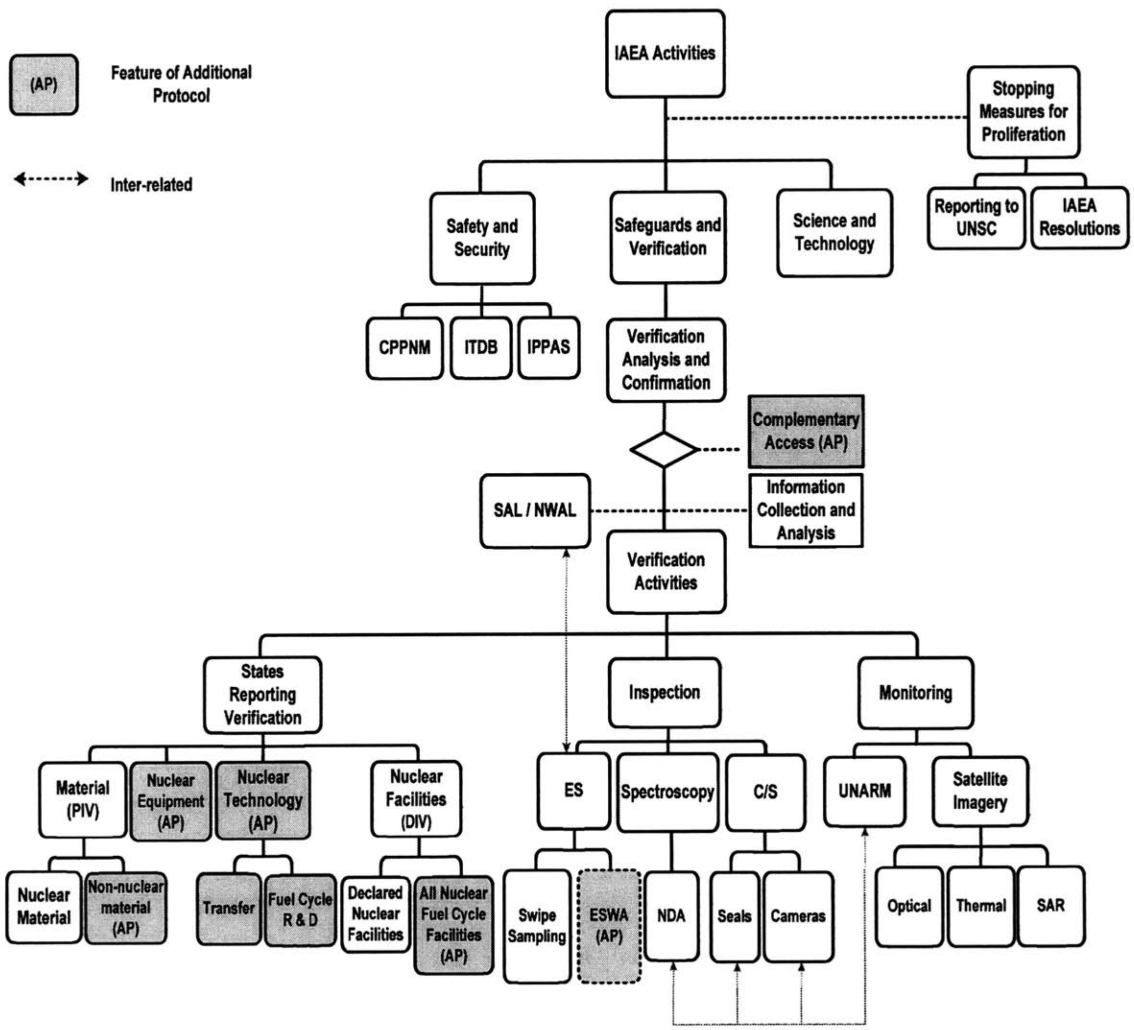

Figure 7.4 IAEA Activities with regard to Safeguards

Table 7.9 shows how long each technology has been applied to safeguards activities by the IAEA. From this Table, it can be noted that the IAEA's technological capabilities have been strengthened by introducing new types of technologies in order to increase effectiveness and efficiency of safeguards.

Table 7.9 Development of Technological Capabilities of the IAEA

	1970s	1980s	1990s	2000s	2010s
C/S					
DA					
NDA					
UNARM					
Swipe sampling					
Satellite					
LCBS					
ESWA			Subject to BOG Approval under Additional Protocol		

Note: The shaded boxes denote that the inspection techniques are applied.

7.13 Summary

The IAEA's capabilities in safeguarding nuclear facilities and detecting proliferation activities were reviewed in Chapters 6 and 7 from a legal and technical perspective, respectively. The IAEA has been strengthening its legal and technical capabilities since 1956 after its establishment. In particular, after the discovery of the Iraqi nuclear weapons program, the IAEA expanded its scope of safeguards measures to include the transfer of nuclear equipment and technology as well as R & D activities with regard to a nuclear fuel cycle.

The IAEA seeks not only generalization of all possible safeguards and security measures but also techniques and procedures that are location- or facility-specific in order to ensure the efficiency and effectiveness of its capabilities. However, the IAEA still seriously lacks capabilities to detect clandestine proliferation activities. Also, it should be noted that technical capabilities of the IAEA may vary, depending on its legal capabilities that facilitate detection activities. This happens because the legal capabilities of any organization can broaden or confine the effectiveness and efficiency of technical capabilities.

PART II MODELING HEU PRODUCTION SCENARIOS AT GCEPS

Part II is dedicated to modeling Highly Enriched Uranium (HEU) production scenarios at Gas Centrifuge Enrichment Plants (GCEPs). Where Part I is a broad analysis of nuclear weapons programs and the NPT regime, Part II narrows the scope to a HEU production stage in a nuclear weapons program and the capabilities of the NPT regime to prevent the production of HEU by proliferators.

In Chapter 8, the general characteristics of Uranium Enrichment Technologies (UETs) were studied. In this chapter, one can understand how uranium is enriched through a variety of UETs, following the conversion of uranium ore concentrates to a proper chemical and physical form. Chapter 9 reviews the technical specifications and characteristics of Gas Centrifuge Enrichment Technology (GCET), the most threatening and efficient UET, associated with nuclear proliferation .

In Chapter 10, the IAEA's approach to safeguarding declared Gas Centrifuge Enrichment Plants (GCEPs) was analyzed. However, there are some limitations in describing the exact specifications of the IAEA safeguards due to security issues with the IAEA and the diversity of GCETs. Through the study on current safeguard approaches, a new conceptual framework for developing future approaches was proposed. In Chapter 11, in order to understand the current issues concerning the difficulty of detecting clandestine GCEPs, the current technological capabilities of the IAEA were analyzed with an extensive literature survey and input from experts.

In Chapters 12 and 13, proliferators' HEU production scenarios using GCEPs were developed, incorporating both technological and legal perspectives. Chapter 12 is dedicated to describing scenarios of acquiring nuclear elements for producing HEU, whereas Chapter 13 focuses on the operation of declared GCEPs for HEU production. Four modes of off-design operation for producing HEU were analyzed.

CHAPTER 8 URANIUM ENRICHMENT TECHNOLOGIES

8.1 Introduction

Uranium Enrichment Technology (UET) produces enriched uranium through separating the U-235 from the U-238. UET used to be regarded as a technology that only a country with the most advanced technology could acquire and operate because UET is delicate and complex. In order to produce HEU for manufacturing nuclear weapons, mined uranium must go through a variety of conversion and enrichment processes. Despite its technological complexity, UET is becoming the preferred means, over Plutonium Reprocessing Technology (PRT), for the creation of weapon materials.

The purpose of this chapter is to analyze what types of UETs are promising for potential proliferators to use for the enrichment of uranium. To this end, this chapter begins with an understanding of why a uranium enrichment program can be preferred over a plutonium reprocessing program for nuclear proliferation. The technological specifications of both a uranium conversion process and a uranium enrichment process are explained. Finally, a comparison of different UETs as potential proliferation risks is provided.

8.2 Why Uranium?

8.2.1 Advantages of a Uranium Enrichment Program

The production of nuclear weapons-grade uranium has always been an expensive and complex process. Therefore, uranium enrichment technology used to be regarded as a technology that a country with a limited industrial and scientific base would find hard to obtain. This was the view until the advent of the Pakistani nuclear weapons program.[376] The success of the Pakistani nuclear weapons program based on uranium enrichment technology demonstrated that the global spread of technological advances allowed the development of a uranium enrichment program to be far easier than in the past.

It is assumed that the uranium enrichment route is a preferred option over the plutonium reprocessing route for several reasons as described in Table 8.1. Despite the fact that uranium enrichment technology is a very complex one that requires a high level of material technology and accuracy; there are some reasons why a state would want to acquire uranium enrichment capabilities and why uranium enrichment technology is preferred over plutonium reprocessing technology. In short, the acquisition of uranium enrichment capability can be explained in terms of completing nuclear fuel cycle and relative advantages over reprocessing plutonium.

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[376] In 1977, U.S. Office of Technology Assessment (OTA) concluded the following; "It is improbable that centrifuge enrichment would be the route take by a country with a limited industrial and scientific base." Jeffrey Lewis, "A Crisis of Confidence " *Bulletin of the Atomic Scientists* 63, no. 1 (January / February 2007).

Table 8.1 Uranium- and Plutonium-based Paths for Nuclear Weapons Programs

Factors	Uranium Enrichment	Preference	Plutonium Reprocessing
Time required	Within a year [a]	Uranium	More than a year [b]
Number of required facilities and its ease to build	Uranium conversion facility UEF	Plutonium	Reactor for irradiating U-238 Spent fuel storage PRF
Material acquisition	Complex uranium enrichment technology	Plutonium	Relatively simple via extraction from reactors rods
Detectability	Very low due to weak environmental signatures Almost impossible to detect small clandestine facilities	Uranium	High due to relatively stronger environmental signatures
Reliability of nuclear weapons	Highly reliable Even without detonation tests Tests are not necessary	Uranium	Must go through nuclear detonation tests
Weapon manufacturability	Straightforward	Uranium	Complex [c]
Cost	Less expensive	Uranium	More expensive[377]

Notes
[a] This refers to conversion time for nuclear material that means the time required to convert different forms of nuclear material to the metallic components of a nuclear explosive device. For more information please see Table I. in IAEA Safeguards Glossary (2001), page 22.
[b] Spent fuel rods from nuclear reactors must be cooled down before they are reprocessed.
[c] For more information, see Chapter 4.

Compared to Plutonium Reprocessing Facilities (PRFs), Uranium Enrichment Facilities (UEFs) have advantages in terms of economics, detectability, manufacturability, and reliability as shown in Table 8.1. For proliferators, it makes more sense and supports a proliferator's position to build UEFs rather than PRFs. First, from an economic point of view, an open fuel cycle is more economic than a closed fuel cycle under the current situation.[378] For proliferators, building UEFs is more presentable to the international community because UEFs are necessary for both closed and open fuel cycles, whereas PRFs are required only in a closed fuel cycle scenario.

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[377] This might vary over different countries. However, according to the MCTL, this is true for the United States, HEU is considered less expensive to use in a weapon than plutonium. U.S. Department of Defense, "Militarily Critical Technologies List (MCTL), Part II: Weapons of Mass Destruction Technologies, Section 5-Nuclear Weapons Technology."

[378] O.E. Aleksandrov, "Comparison of Two Approaches to Using the Averaging Method for Analyzing Separation in a Gas Centrifuge," *Atomic Energy* 94, no. 4 (2003).

Second, from a technical point of view, solely considering the fissile material production technique itself, uranium enrichment might be considered more complex. However, considering the whole nuclear fuel cycle for each route, it is estimated that the complexity of uranium enrichment technology can be offset by the straightforwardness of uranium weapon manufacturability.[379] In addition, the acquisition of weapons-usable plutonium is much more complicated because it requires a large number of fuel assemblies and massive shielding requirements during transportation and reprocessing of spent fuels.[380] Third, from a viewpoint of detectability, even though there have been improvements in the efficiency of environmental detection, it is still challenging to detect uranium enrichment facilities with regard to the cost and efficiency of those safeguards.

8.2.2. Uranium Enrichment Capability and Nuclear Weapons Programs

Most states want to acquire uranium enrichment technology, analogous to nuclear proliferation propensity, for national security, energy security, and economic benefit purposes. It is obvious that a state with a uranium enrichment capability can manufacture a nuclear weapon in a shorter duration than a state with no such capability. This capability can play a role in deterrence against surrounding states. As for energy security, if a state has nuclear reactor facilities, either possession of its fissile material production capacity or acquisition of a fuel supply guarantee from another state must be obtained to ensure sustainable operation. However, the former option seems to be more attractive in reality. As for economic benefits, if a state has uranium mines, a state can obtain a higher economic benefit by producing more qualified product with uranium enrichment facilities or by not importing qualified products of uranium. All nuclear weapons states have developed both plutonium and uranium-based programs. In contrast, India, Israel, Pakistan, and North Korea dedicated their efforts to one path after they had spent a while exploring both pathways. Recently-known proliferators, Iran and Libya, sought uranium-based nuclear weapons. Table 8.2 shows the relationship between the possession of uranium enrichment program and fissile material used for a nuclear weapons program.

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[379] U.S. Department of Defense, "Militarily Critical Technologies List (MCTL), Part II: Weapons of Mass Destruction Technologies, Section 5-Nuclear Weapons Technology."

[380] Victor Bragin, John Carlson, and Ressell Leslie, "Building Proliferation-Resistance into the Nuclear Fuel Cycle" (paper presented at the International Seminar on Status and Prospects for Small and Medium Sized Reactors, Cairo, Egypt, May 27-31 2001).

Table 8.2 Relationship between Nuclear Facilities and Nuclear Weapons Program[381]

Country	Material used for weapons program		Commercial uranium enrichment program	Comments on uranium enrichment program
	Pu	HEU		
US	O	O	O	Full scale production plants
Russia	O	O	O	Full scale production plants
UK	O	O	O	Full scale production plants
France	O	O	O	Full scale production plants
China	O	O	O	Full scale production plants
India	O	X	X	Experimental enrichment program
Israel	O	X	X	Experimental enrichment program
South Africa	X	O[382]	O	Full scale production plants
Pakistan	Δ[383]	O	X	· Full scale production plants
Iran	Δ[384]	O	X	Pilot plants
NK	O	Δ[385]	X	R & D Projects
Iraq[386]	O	O	X	Experimental program

Note: O = possess a program, X = not possess a program, and Δ denotes that the information about the program is not confirmed.

Some might argue that HEU can be purchased to make a nuclear weapon without uranium enrichment facilities being installed. But, it is necessary to build UEFs for proliferators. First, proliferators need more than several SQs to be a de facto nuclear weapons state, because a couple of nuclear warheads is not enough to exploit effective nuclear tactics, such as a second-strike capability. Second, some loss of uranium material is unavoidable during the warhead manufacturing process and detonation testing, as necessary. In this regard, a proliferator should acquire HEU production capabilities rather than simply acquiring smuggled fissile material for the sustainability of a nuclear weapons program. It does not seem feasible to obtain several SQs of HEU via purchase.

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381 Arjun Makhijani, Lois Chalmers, and Brice Smith, "Uranium Enrichment: Just Plain Facts to Fuel an Informed Debated on Nuclear Proliferation and Nuclear Power," (Tacoma Park, MD: Institute for Energy and Environmental Research for the Nuclear Policy Research Institute (IEER), 2004). Table 1: Nuclear Weapons States-Uranium Enrichment, Military and Commercial, p.17.

382 "South African Enrichment Program," (Central Intelligence Agency, Aug. 1977).

383 Zhang, "IAEA-SM-367/16/01". Pakistan has a heavy water reactor at Khustan reactor site and a gas centrifuge enrichment plant at Khuhuta.

384 Iran has heavy water research reactor project at Arak. David Albright and Jacqueline Shire, "A Witches' Brew? Evaluating Iran's Uranium-Enrichment Progress," review of Reviewed Item, *Arms Control Today*, no. (Nov. 2007), http://www.armscontrol.org/act/2007_11/Albright.

385 Paul Kerr, "N. Korea's Uranium-Enrichment Efforts Shrouded in Mystery," *Arms Control Today* (May 2003).

386 Albright and Shire, "A Witches' Brew? Evaluating Iran's Uranium-Enrichment Progress," review of Reviewed Item, no.

8.3 Overview of Uranium Hexafluoride Production

8.3.1 Production of Yellow Cake

The final output of the uranium mining and milling process is U_3O_8, called yellow cake [or Uranium Ore Concentrate (UOC)]. However, yellowcake is not pure U_3O_8, and it typically contains 65 to 68 percent uranium by weight. Other components include uranium dioxide (UO_2) and uranium trioxide (UO_3). The milling process consists of: leaching to bring uranium present in the solid matrix into solution; concentration and purification of the dissolved uranium; and precipitation of the concentrated and purified dissolved uranium into a suitable chemical intermediate. Leaching is at the heart of the milling process, and ***acid-leaching*** and ***alkaline-leaching*** techniques are most commonly used. Ammonium diuranate (ADU)[$(NH_4)_2U_2O_7$] is produced via the acid-leaching technique which uses sulfuric acid (H_2SO_4) as a leachant and sodium chlorate ($NaClO_3$) as an oxidizing agent. Sodium diuranate ($Na_2U_2O_7$) is produced through alkaline-leaching with sodium carbonate (Na_2CO_3).[387]

8.3.2 Conversion of Yellow Cakes

The chemical form produced from uranium milling plants is U_3O_8. For enrichment operation, uranium must be prepared in appropriate forms.[388]

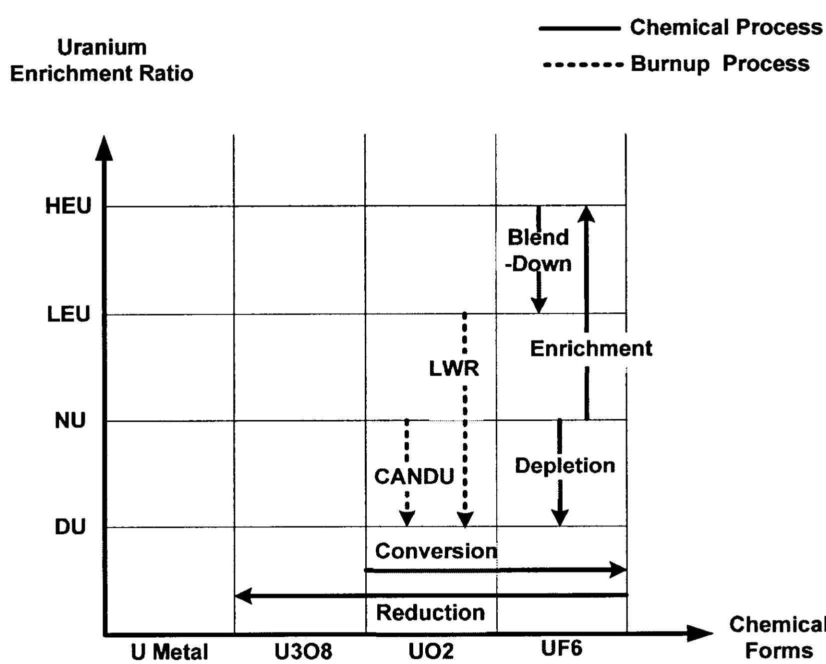

Figure 8.1 Degrees of Freedom of Uranium Material[389]

[387] Chiranjib Kumar Gupta and Harvinderpal Singh, *Uranium Resource Processing: Secondary Resources* (New York, NY: Springer, 2003)., pp.89-105.

[388] UF_6 and UCl_4 are the principal compounds used as inputs to uranium enrichment processes. More specifically, gaseous UF_6 is used as the feed in the GCEP and GDP, and UCl_4 is used as the feed in the EMIS process.

Figure 8.1 shows how uranium-containing material changes its chemical forms and Uranium Enrichment Ratio (UER). As can be seen, there is no way to change both UER and the chemical form. Here, I will focus on the conversion process from U_3O_8 to UF_6 because UF_6 is the form on which most uranium enrichment facilities operate.

A conversion process has two objectives: (i) the chemical conversion of U_3O_8 to UF_6 and (ii) the removal of impurities. In other words, during a conversion process, impurities are removed and the uranium is combined with fluorine to create the UF_6 gas.[390] The purification process is necessary because yellowcake typically contains 65 to 80 percent uranium by weight and up to 20 percent extraneous impurities. Two commercial processes are used for the conversion of uranium from Uranyl Nitrate Solution or Uranium Nitrate Hexahydrate (UNH), $[UO_2(NO)_3)_2 \cdot 6H_2O]$ to UF_6. These are the ***wet process*** and the ***dry process***, respectively. Table 8.3 and Figure 8.2 show the overall schematic of uranium conversion process.

Table 8.3 Chemical Equations for Uranium Conversion Processes [Settle (2005)][391]

Reactions	Chemical Equations
$U_3O_8 \rightarrow UO_2(NO_3)_2$	• $U_3O_8+8HNO_3 \rightarrow 3UO_2(NO_3)_2+2NO_2+4H_2O$
$UO_3 \rightarrow UO_2$	• $UO_3+H_2 \rightarrow UO_2+H_2O$ (in a kiln) or UO_3+NH_3 (cracked) $\rightarrow UO_2+H_2O$
$UO_2 \rightarrow UF_4$	• UO_2+4HF(gaseous) $\rightarrow UF_4+2H_2O$ (in a kiln at 300-500°C)
	• UO_2+4HF(aqueous) $\rightarrow UF_4+2H_2$
$UO_2 \rightarrow UCl_4$	• CCl_4 (Carbon tetrachloride) at 700 °F
$UF_4 \rightarrow UF_6$	• $UF_4+ F_2 \rightarrow UF_6$ (in a tower reactor or fluidized bed reactor)
$UO_2 \rightarrow UF_6$[392]	• $UO_2+3F_2 \rightarrow UF_6+O_2$

Note: U_3O_8 is dissolved in nitric acid and extract using a solvent such as tributyl phosphate.

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389 HEU blenddown methodology is well described in Kevin Alldred, "Russian HEU Blend-Down Technology and Options for Expansion" (paper presented at the 49th Annual Meeting of INMM, Nashville, TN, July 13-17 2008).. Metallic uranium must be transformed into HEU oxides and then HEU UF6. Finally, HEU UF_6 is blended with LEU UF_6 to achieve lower level of uranium enrichment ratio.

390 The quality of UF_6 is crucial for ensuring more successful uranium enrichment operation. Iran used stocks of high-quality uranium gas imported from China in order to hasten a breakthrough in enrichment. Low quality of UF_6 that contains contaminants can cause centrifuges to crash.

391 Frank Settle, *Nuclear Chemistry Uranium Production* (Chemcases.com, 2005 [cited Nov.13 2008]).

392 Victor Galinsky et al., "A Fresh Examination of the Proliferation Dangers of Light Water Reactors," (The Nonproliferation Education Center, Oct. 2004)., p.41.; and Direct process A can be made using fluorine gas or chlorine trifluoride (ClF3).Ayyub, "Uncertainties in Expert-Opinion Elicitation for Risk Studies".. Direct process A can be made using fluorine gas or chlorine trifluoride (ClF3), especially at small size facilities.

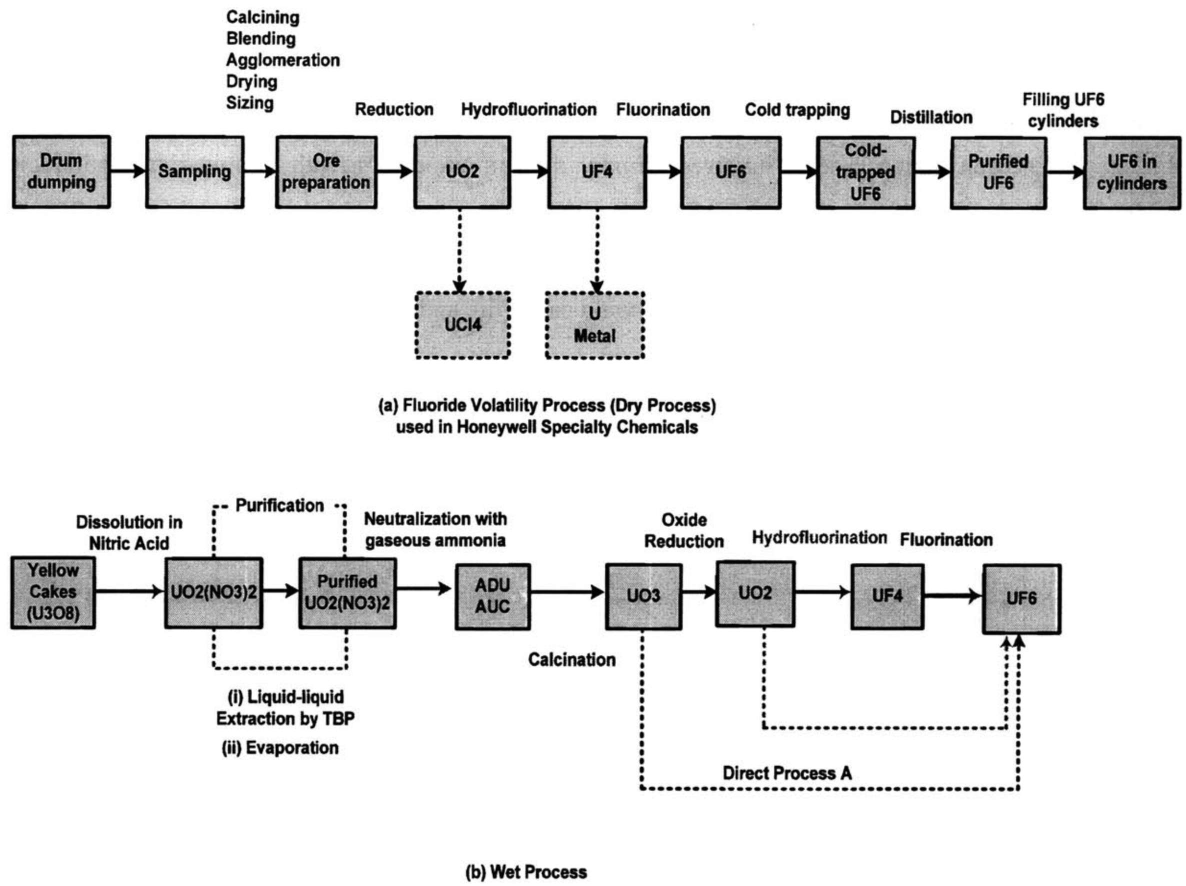

Figure 8.2 Uranium Conversion Process from Yellow Cakes to UF_6 Gas[393]

8.3.3. Reduction of Uranium

A. UF_6 to UO_2

The inverse process of UF_6 to UO_2 or uranium metal is called ***reduction***.[394] A proliferator must go through this process after the completion of uranium enrichment to make nuclear warheads. There are three possible techniques to reduce UF_6 to UO_2 as shown in Figure 8.3: Integrated Dry Route (IDR), Ammonium Diuranate (ADU), and Ammonium Uranyl Carbonate (AUC). In the IDR, UF6 is reduced and hydrolyzed using hydrogen and steam. In the ADU process, UF_6 is hydrolyzed in water, and

[393] A process through ADU or AUC is used at small size plants (100 MTU/year), whereas the thermal denitration process is favored by medium (100 to 1000 MTU/year) and large plants (1,000 to 10,000 and higher MTU/year). R. L. Faulkner et al., "Oak Ridge Efforts to Enhance Conversion Plant Safeguards" (paper presented at the INMM 45th Annual Meeting Proceedings of the Institute of Nuclear Materials Management, Orlando, FL, July 2004). And U.S. Department of Defense, "Militarily Critical Technologies List (MCTL), Part II: Weapons of Mass Destruction Technologies, Section 5-Nuclear Weapons Technology." ADU is produced through neutralization with gaseous ammonia and followed by filtering, drying and calcining. Ayyub, "Uncertainties in Expert-Opinion Elicitation for Risk Studies".

[394] For more detailed information about plants and equipment for the conversion and reduction of uranium, see Nuclear Transfer and Supplier Policy Division U.S. Department of Energy, *Handbook for Notification of Exports to Iraq: Annex 3* (Apr 1998 [cited Nov.11 2008]); available from <http://www.iraqwatch.org/government/US/DOE/DOE-Annex3.htm>..

ammonia is added to precipitate ADU. ADU is reduced with hydrogen at 820 °C. In the AUC process, UF_6, CO_2, and NH_3 are combined in water thereby precipitating AUC. AUC is combined with steam and hydrogen at 500-600 °C.

The conversion process involves primary risks in association with chemical and radiological impacts. Strong acids and alkalis, which are used in the conversion process to convert the yellowcake powder to very soluble forms, may lead to possible inhalation of uranium. In addition, conversion produces extremely corrosive chemicals that could cause fire and explosion hazards.[395]

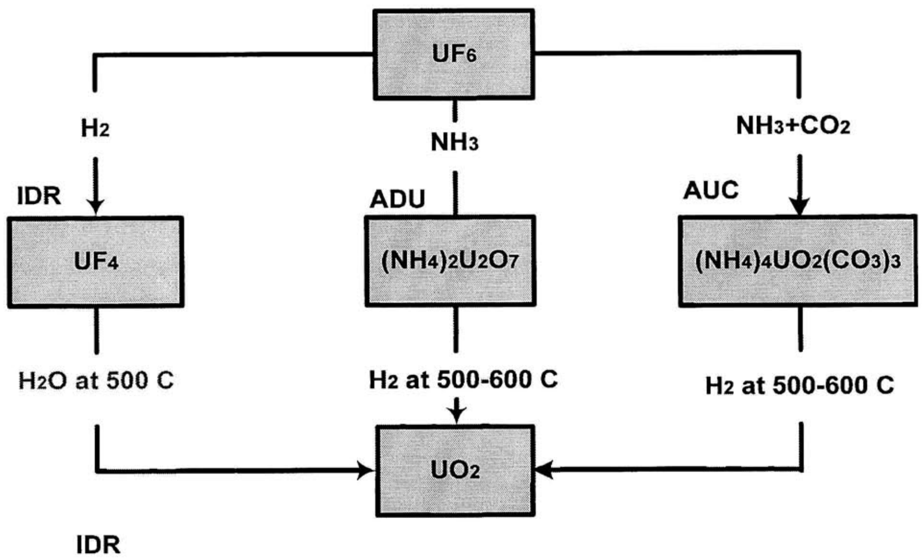

Figure 8.3 Process of Reduction from UF_6 to UO_2[396]

B. Production of Uranium Metal

For enriching uranium using AVLIS technique or manufacturing nuclear bombs, UF_4 needs to be converted to uranium metal by reduction with magnesium (large batches) or calcium (small batches) at temperatures above the melting point of 1130 ° C. The chemical equations are as follows: [397]

$$(UF_4)_s + 2(Ca)_s \rightarrow U_s + 2(CaF_2)_s \qquad (8.1)$$

$$(UF_4)_s + 2(Mg)_s \rightarrow U_s + 2(MgF_2)_s \qquad (8.2)$$

[395] The United States only uranium conversion plant is in Metropolis, IL. U.S. Nuclear Regulatory Commission, *Uranium Conversion* (May 10 2005); available from http://www.nrc.gov/materials/fuel-cycle-fac/ur-conversion.html. Canada, France, United Kingdom, China, and Russia also have uranium conversion plants.

[396]OECD Nuclear Energy Agency (NEA), *The Safety of the Fuel Cycle*, 3rd ed. (Paris, France: OECD, 2005)., pp. 31-32; and G. A. Stoetzel et al., *Radiological Health Ascpect of Commercial Uranium Conversion, Enrichment, and Fuel Fabrication, PNL-4438 USUR-03* (Nov. 1982).

[397]Ayyub, "Uncertainties in Expert-Opinion Elicitation for Risk Studies". For magnesium at 600 ° C from R. Rogers, K. Seddon, and S.Volkov, *Green Industrial Applications of Ionic Liquids* (Boston, MA: Kluwer Academic Publishers, 2002)., pp.210-211.

8.3.4 Treatment of UF_6

A. Properties of UF_6

UF_6 is a highly corrosive material. It is a strong fluorinating agent and reacts violently with water, many organic compounds, and many metals except for Ni, Al, or their alloys.[398] At the final state of uranium conversion process, UF_6 gases pass through a cold trap and are cooled to -10 ° C. At an interim storage place, UF_6 is stored in the form of liquid or solid. However, UF_6 should be sublimated before enrichment operation. As shown in Figure, at atmospheric pressure, solid UF_6 transforms directly to UF_6 gas (sublimation) when the temperature is raised to 134° F (57° C), without going through a liquid phase. On the contrary, after operation, gaseous UF_6 should be deposited from gas to solid or condensed from gas to liquid for storage and transportation.

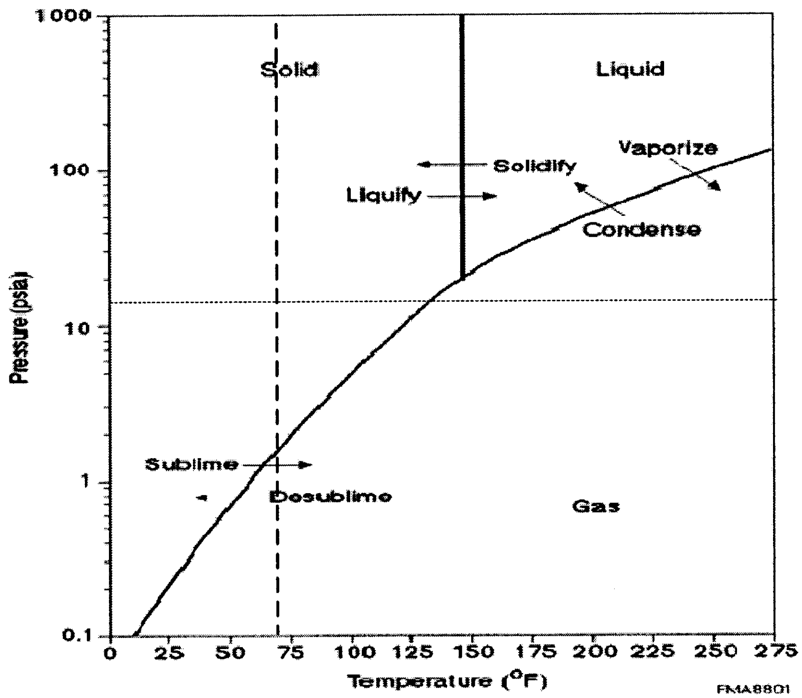

Figure 8.4 Phase Diagram of UF_6

B. Transport of UF_6

After the completion of the conversion process, UF_6 is then pressurized and cooled to a liquid. The liquid state of UF_6 is drained into specially designed thick-walled steel shipping cylinders. As the liquid UF_6 within the cylinder cools, it becomes a white crystalline solid in approximately five days and is then shipped to an enrichment plant in solid form. Table 8.4 list types of cylinders for transporting UF6.

398 Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation* (New York, NY: Taylor & Francis, 1983)., pp.116-119.

Table 8.4 Types of Cylinders for UF_6[399]

Size	Type (Model)	Size	Capacity	
			Weight	**Enrichment**
Small	1S,2S,5A,5B,8A,10A,12A,12B	1S (1.5 inch)[a]	230 kg (500 lb) of UF_6	HEU
		5A (5 inches)	25 kg	HEU (5A)
Medium	30A, 30B	30 inches (D) and 7 feet (L)	2.5 tons solid UF6	LEU (4.95% U-235)
Large[400]	48OH, 48OHI, 48HX, 48H, 48O, 48OM	48 inches	14 tons	Below LEU
	48 Y[401]	48 inches (D) and 12 feet (L)	14 tons of solid UF6	1.0% of U-235 (NU)[402]
	48 G			Depleted Uranium
	48A, 48 X, 48T	48 inches (D) and 10 feet (L)	10 tons of solid UF6	4.5% of U-235

Notes
[a] Cylinder type designations generally correspond to the approximate diameter of the cylinder, except for 1S and 1S, which are 1.5 and 3.5 inches, respectively.
[b] 48 X and 48 Y are made of carbon steel (A-516) at a nominal thickness of 5/8 inch.

8.4 Overview of Uranium Enrichment

8.4.1 Separative Work Unit (SWU)

In order to understand uranium enrichment, the concept of **Separative Work Unit (SWU)**[403] must be understood. The SWU is a unit of measure indicating the physical effort or the work required for a certain degree of enrichment. In other words, the value of SWUs quantifies the resources required to perform the enrichment operation to the desired product level. It should be noted that the SWU is determined under given values of waste concentration and feed concentration. A cascade has three

[399] B.M. Biwer et al., "Transportation Impact Assessment for Shipment of Uranium Hexafluoride (UF6) Cylinders from the East Tennessee Technology Park to the Portsmouth and Paducah Gaseous Diffusion Plants," (Argonne, IL: Argonne National Laboratory, Oct. 2001). Table 1-2, p.1-8.

[400] "UF6 Cylinder Program System Requirements Document," (Lockheed Martin Energy Systems, Nov. 1995). Figure 4, p.23. Each model is differently designed in terms of weight capacity, wall thickness (think or thin), and the possession of skirts.

[401] There are about 100,000 48 Y UF_6 cylinders in the world, nearly 80,000 in the U.S. and about 10,000 in France. WISE News Communique, *Rupture of UF_6 Cylinder* (1998 [cited Jan. 3 2009]); available from http://www10.antenna.nl/wise/index.html?http://www10.antenna.nl/wise/487/4836.html.

[402] Moody, Hutcheon, and Grant, *Nuclear Forensics Analysis.*, p.98; D.G. O'Connor, A.B. Poole, and J.H. Shelton, "Assessment of Reusing 14-Ton Thi-Wall, Depleted UF6 Cylinders as Llw Disposal Containers," (Nov. 2000). The tails of the enrichment process are stored in steel drums on-site at UEFs. These drums are effectively self-sealing.

[403] Sometimes this is called Separative Power with the nomenclature of δU.

streams of material; the feed material (F), the waste or tails material (W), and the product material (P). The SWU is defined as the following equation:

$$SWU = P \bullet V(x_p) + W \bullet V(x_w) - F \bullet V(x_f) \qquad (8.3)$$

where P, W, F are the amounts of the product, the waste, and the feed; x_p, x_w, *and* x_f are weight fractions of U-235 in the product, the waste, and the feed materials; and V(x) is a value function that takes the form of

$$V(x) = (2x-1) \cdot \ln\left(\frac{x}{1-x}\right) \qquad (8.4)$$

the V(x) values are dimensionless and are known as "**separation potentials**", so the units of SWU can be in terms of any amount of material. The value function V(x) is dimensionless, so the unit of SWU is contingent on the units of P, W, and F.

In the calculation of SWUs needed for the enrichment, the number of SWUs expended per unit product is commonly used, which is described as the following equation:

$$SF = \frac{SWU}{P} = V(x_p) + \frac{x_p - x_f}{x_f - x_w} V(x_w) + \frac{x_p - x_f}{x_f - x_w} V(x_f) \qquad (8.5)$$

SWU/P is dimensionless, and it is also known as SWU Factor (SF).

The units of SWU-related nomenclatures are often confused. This is because SWU is meant to measure the work required during the enrichment process, whereas the value of SWUs is given in terms of kilograms or tons because P, W, and F are described in units of kilograms, according to equation 8.3. In practice, either kg-SWUs or metric ton-SWUs are the preferred ways to denote that it is the unit for SWUs. In the description of an UEF capacity, a time period that SWUs are expended should be taken into consideration. Thus, a capacity of UEFs is expressed in terms of kg-SWUs per year or ton-SWUs per year.

Table 8.5 and Figure 8.5 show the relationship between the use of SWU and the degree to which uranium is enriched. For example, if one wants to produce 93 percent Weapons-Grade Uranium (WGU) with 0.72 percent Uranium Enrichment Ratio (UER) of uranium feed, a mass of 197.34

kilograms and 214.03 SWU are required in theory. However, during the enrichment process, the loss of SWU is inevitable.

Table 8.5 Requirements to Produce 1kg of 93 % WGU per Different UER of Feed[404]

Feed UER [%]	Mass required [kg]	SWU required	Feed UER [%]	Mass required [kg]	SWU required
0.72	197.34	214.03	**30**	3.12	13.78
1	123.67	176.30	**40**	2.33	9.98
2	53	114.08	**50**	1.86	7.38
3	33.73	87.04	**60**	1.55	5.39
5	19.53	60.88	**70**	1.33	3.74
10	9.51	36.23	**80**	1.16	2.23
20	4.70	20.34	**90**	1.03	0.6

Note: UER = Uranium-235 Enrichment Ratio

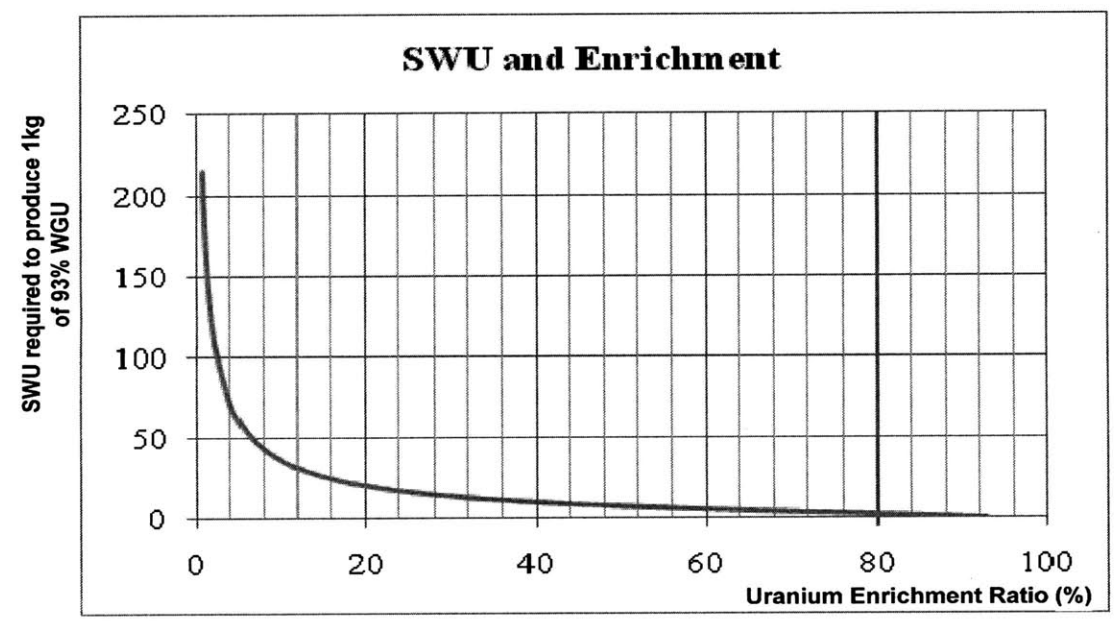

Figure 8.5 Relationship between Required SWU and the UER of Feed Used in Producing 1 kg of 93% WGU

404 xw=0.0025 and xp=0.93 are assumed for the analysis.

8.4.2 Terms and Parameters with regard to Uranium Enrichment

Understanding terminology regarding uranium enrichment operation is necessary in the analysis of enrichment operation. Parameters are classified into separation, mass, reflux, and time-related terms.

A. Separation and Mass

For the enrichment of any isotope, the enrichment element in the flow process diagram can be treated as a 'black box' that changes an isotopic composition of a mixture between two different isotopes. To fully quantify the enrichment operation a mixed input goes into the "black box" element, i.e., 'feed', 'product' and the output 'tails' or 'waste' come out of the element. Table 8.6 shows separation- and mass related-terms for describing uranium enrichment.

Table 8.6 Important Parameters for Uranium Enrichment I [SIPRI (1983) and Villani (1983)]

Term		Definition
Separation	Relative isotopic abundance (R)	$R = \frac{N}{(1-N)}$, N refers to the percentage composition in numbers of molecules of the desired isotope (U-235), whereas (1-N) refers to the fraction of U-238.
	Single-stage separation factor (q)	$q = \frac{R_{enriched}}{R_{depleted}}$, $R_{enriched\ or\ depleted} = \frac{mole\ fraction\ of\ U_{235}}{(1 - mole\ fraction\ of\ U_{235})}$
	Stage enrichment factor (α)	$\alpha = \frac{R_{n+1}}{R_n}$ where R_n=UER entering stage n, R_{n+1}=UER going out of stage n.
	Separation gain (g)	$g = q - 1$
	Enrichment gain	$\varepsilon = \alpha - 1$
Mass	Total mass flow rate (L_{total})	$L_{total} = (\frac{8}{g^2})\Delta V$, ΔV=total separative work
	In-process inventory or hold-up (I)	The amount of uranium present in any given stage or in the full cascade $I = (\frac{8t_h}{g^2})\Delta V = L_{total} \times t_h$, where t_h = hold-up time, g = separation gain
		Nuclear material deposits remaining after shutdown of a plant in and about process equipment, interconnecting piping, filters and adjacent work areas[405]

[405]Sharikov, "Verification Challenges for Safeguarding Uranium Enrichment Plants.", pp. 75-79.

B. Parameters for Uranium Enrichment

Table 8.7 describes important parameters for uranium enrichment. The required time and the desired level of enrichment are amongst the most important considerations in uranium enrichment process. Therefore, reflux ratio is an important parameter because it can be adjusted by the operator inputs throughout the process. Reflux ratio refers to the ratio of the amount of flow extracted or produced to the amount of flow recycled.

Table 8.7 Important Parameters for Uranium Enrichment II [Krass et al., (1983)]

Term		Definition
Reflux	Reflux ratio	$Reflux\ ratio = \frac{Poduct\ withdrawal}{Countercurrent\ flow}$
	Reflux loss	Percentage of the uranium loss in the reflux process
	Total Reflux	Operating condition where no product is extracted (with no product removal)[406]
Time	Flushing time	The time required to flush out UF_6 in a gas centrifuge machine
	Equilibrium time	(i) The time from the initial start-up to the point at which the product flow rate reaches half of its *asymptotic value*. Conventionally defined as the time from the initial start-up to the point at which the product flow rate reaches half of its asymptotic value. (ii) The time required to reach the equilibrium concentrations at every point of the cascade.[407] $t_e = \frac{8t_h}{g^2} E(N_P, N_F)$, where E is multiplying constant, N_P and N_F are enrichment ratios of the product and feed
	Cascade fill time	The time to fill the cascade for the operation with new feedstock.
	Stage hold-up time (transit time)	The time for taking a given sample of material to pass through a single stage, and determined by the specific design of the separating elements. This is necessary information to calculate the plant equilibrium time and inventory.[408]

Notes
[a] Reflux is defined as either the portion of the stage flow at the top of a stage or a cascade which is sent back down the stage.
[b] Countercurrent flow means a form of internal reflux which causes a continual recirculation of the gas in the centrifuge.

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[406] Amnon Kohen and Hans Heinrich Limbach, *Isotope Effect in Chemistry and Biology* (Boca Raton, FL: CRC Press, 2006). p.63. This term is adopted from the old technique of fractional distillation.
[407] Stelio Villani, *Isotope Separation* (Hinsdale, IL: American Nuclear Society, 1976)., p.134.
[408] Gregory S. Jones, *Iran's Centrifuge Enrichment Program as a Source of Fissile Material for Nuclear Weapons* (Nonproliferation Policy Education Center, April 8 2008 [cited Feb.3 2009]); available from http://www.npec-web.org/Frameset.asp?PageType=Single&PDFFile=20081017-Jones-IranEnrichment&PDFFolder=Essays.

8.5 Gas Centrifuge Enrichment

8.5.1 Introduction

Lindermann and Aston first suggested the use of gas centrifugation for the separation of isotopes in 1919. The uranium enrichment industry in the Soviet Union was created at the end of the 1940s to produce WGU. An Austrian scientist Zippe worked on gas centrifuge technology in the Soviet Union and he got involved in the American project after coming to the University of Virginia in 1956. [409]He continued development and then his work resulted in the success of a new advanced centrifuge technology later used in the US and the Urenco states.

Centrifuges have evolved from a variety of materials, with varying lengths, diameters, and operating speeds. [410] The U.S. installed more than 1,300 centrifuges at Portsmouth with fiberglass rotors with some limitations in 1985. In 1999, USEC began exploring potential deployment of a GCEP to replace gaseous diffusion. The most recent design of the USEC is called "American Centrifuge" and USEC is developing technology in cooperation with Oak Ridge National Laboratory (ORNL).[411] As of 2004, the world total enrichment capacity available is estimated to be 53,500 tSWU/yr and gas centrifuge accounts for about half, 23,000 tSWU/yr.[412]

8.5.2 Principles

The gas centrifuge uses convective diffusion, with strong accelerations to magnify the effect. The gas centrifuge chamber is a hollow cylindrical tube and it rotates on its axis at very high speeds. As the cylinder rotates at very high speed, the UF_6 gas is separated into the two isotopic concentrations through the weight differences. The gas is accelerated by rapid rotation and creates a centrifugal force. The centrifugal force accelerates particles towards the periphery of the circle; hence, it separates uranium isotopes because of the variation in atomic mass. A schematic drawing and the functions of the various parts of a gas centrifuge are given in Figure 8.6 and Table 8.8.

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[409] Beginning in the mid-1950s (1955), the U.S. Atomic Energy Commission began supporting significant developmental work on gas centrifuge technology. B. McGinnis et al., "Gas Centrifuge Uranium Enrichment Facilities in the United States-IAEA Safeguards Implementation" (paper presented at the 46th Annual Meeting of INMM, Phoenix, AZ, July 10-14 2005).

[410] H.G. Wood, A. Glaser, and R. S. Kemp, "The Gas Centrifuge and Nuclear Weapon Proliferation," *Physics Today* (Sep. 2008)., pp. 40-45.

[411] ORNL, "Gas Centrifuge Research Comes Home to Oak Ridge," *ORNL Reporter*, no. 48 (May 2003).

[412] M. D. Laughter, "Profile of World Uranium Enrichment Programs - 2007, ORNL/TM-2007/193," (Oak Ridge National Laboratory, 2007). The gaseous diffusion plants in France and the US are supposed to be replaced by gas centrifuge facilities.

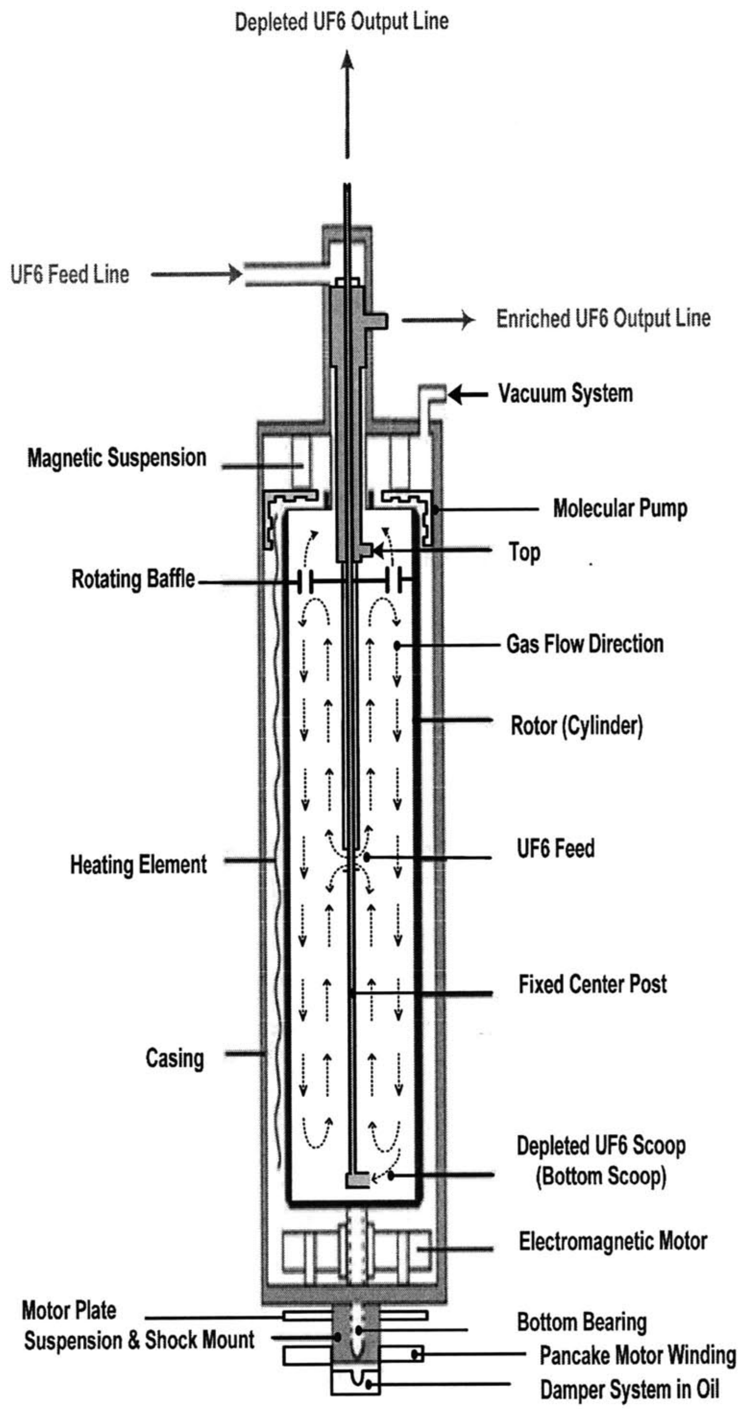

Figure 8.6 Schematic Drawing of Gas Centrifuge Separation Chamber [413]

[413] For more information concerning the properties of a hypothetical centrifuge, see Table 6.2 Properties of a hypothetical centrifuge in Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation*. p.133.

Table 8.8 Main Parts and Functions of Centrifuges [GlobalSecurity.org][414]

Main parts	Function
Top and bottom bearing	•Stabilization of the rotor in the presence of radial rotor vibrations. •Prevention of contact between feed spindle and rotor
Suspension system	•Damping of rotor vibration.
Electric power supply	•Provision of an AC output to gas centrifuge drive motors
Frequency converters	•Conversion of AC input at the 50-6 Hz from the electric power grid to a much higher frequency (typically 600 Hz or more)(the speed of an AC motor is proportional to the frequency of the supplied current)
Bellows	•Bellows make rotor tubes connected together. •Either triangular or rectangular shape[415] •A specialized Urenco-designed component made from maraging steel. These are thin-walled cylindrical pieces that act as a type of spring, allowing the rotor to bend ever so slightly and avoid breaking during start-up and shutdown.[416]
vacuum system	•Friction prevention and thermal isolation[417]
Baffles	•Promotion of the reflux flow along the end plates.[418] •Prevention of countercurrent generation opposing the one produced by the bottom scoop by shielding the top scoop from the main gas flow[419]
Casing	•Protection of rotor from external shocks •Maintenance of vacuum
Heating wire	•Overall temperature control to maintain gaseous phase of UF6 •Generation of thermal drive for counterflow generation
Molecular pump	•Knock UF6 molecules back into interior of rotor using high speed rotating blades[420]

[414] GlobalSecurity.org, *Gas Centrifuge Uranium Enrichment* ([cited 2009 Jan. 15]); available from http://www.globalsecurity.org/wmd/intro/u-centrifuge.htm.
[415] Tsunetoshi Kai, "Basic Characteristics of Centrifuges (IV)," *Nuclear Science and Technology* 14, no. 3 (Jul. 1977)., pp.506-518.
[416] Albright and Shire, "A Witches' Brew? Evaluating Iran's Uranium-Enrichment Progress," review of Reviewed Item, no.
[417] Karl Cohen, *The Theory of Isotope Separation as Applied to the Large Scale Production of U-235*, 1st ed. (New York: McGraw-Hill Boo Co., 1951).
[418] Kai, "Basic Characteristics of Centrifuges (IV)."
[419] Donald R. Olander, "The Theory of Uranium Enrichment by the Gas Centrifuge," *Progress in Nuclear Energy* 8 (1981)., pp. 1-33.
[420] Robert F. Mozley, *The Politics and Technology of Nuclear Proliferation* (Seattle, WA: University of Washington Press, 1998)., p.103

8.6 Laser Enrichment Technology (LET)

8.6.1 History

Research on laser isotope separation technologies began in the early 1970s as a third-generation enrichment technology because it can produce HEU far more effectively than gas centrifuge technology of the second-generation.[421] Laser enrichment technology has significant advantages over other enrichment technologies in terms of low electricity consumption[422] and low capital costs. During the 1980s and 1990s the US, France, Britain, Germany, South Africa, Japan and possibly Russia attempted to develop laser enrichment technology, but all failed because of its technical complexity. It is known that US efforts involved 500 scientists and spent around 2 billion dollars on three different laser enrichment projects:[423]

- Atomic Vapor Laser Isotope Separation (AVLIS) based on selective photoionization by Lawrence Livermore National Laboratory (LLNL) and Jersey Nuclear-AVCO Isotopes (JNAI) in the 1970s
- Molecular Laser Isotope Separation (MLIS) based on photo-dissociation by a group of scientists at the Los Alamos National Laboratory (LANL) in 1971, and
- Plasma process by TRW Corporation

The US, Japan, and France did research on both MLIS and AVLIS. Major enriching counties like the US and France was in favor of AVLIS while MLIS was being pursued in other countries such as Germany and the UK. But most countries terminated their MLIS development program, except for South Africa and Japan.[424] Continued research in AVLIS in Australia resulted in a very promising technology, the so-called SILEX technology.[425]

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[421] William Metz, "Laser Enrichment: Time Clarified the Difficulty," *Science, New Series* 19, no. 4232 (Mar 1976)., pp. 1162-1163+1193.

[422] Great savings in energy 1000 times less than gaseous diffusion plants (GDPs) and 100 times less than the gas centrifuge enrichment plants (GCEPs).

[423] Richard Macey, *Laser Enrichment Could Not Cut Cost of Nuclear Power* (The Sydney Morning Herald, May. 27 2006 [cited 2009 Mar. 18]); available from http://www.smh.com.au/news/national/laser-enrichment-cut-cost-of-nuclear-power/2006/05/26/1148524888448.html.

[424] Ann MacLachlan, "South Africa's Aec Plans to Test Prototype Mlis Enrichment in Unit 1994," *Nuclear Fuel* 17, no. 5 (1992). South Africa planned to test economic and technical parameters of a prototype uranium enrichment unit using MLIS around 1994 and had stated that their MLIS program was ready to be deployed for LEU production.

[425] Maurice Lenders, "Uranium Enrichment by Gaseous Centrifuge" (paper presented at the Annual Meeting on Nuclear Technology 2001, Dresden, Germany, May. 16 May 2001)., p.7. Urenco was aware of the prospective benefits of laser enrichment and carried out significant research at a cost of some 300 million dollars. However, MLIS and AVLIS were terminated in 1992 and 1994 respectively, the reason being that the technology could not be justified on a commercial scale. Urenco had no need of a new technology, because it was very optimistic about the future of the gas centrifuge. Urenco focused on its advanced centrifuge while maintaining a watching brief on laser enrichment technology.

Laser enrichment techniques will pose a significant threat to nonproliferation, if it is developed and commercialized which is currently the case. It is generally estimated that the transition from a physical principle to an economically viable industrial technique is usually hard. But the basic physical principles are really quite simple, and all have been understood for many years. It allows the construction of a small facility thanks to its large separation factors. In addition, a small size of components and highly energy-efficient operation enable clandestine operation of HEU production. Generally, a laser enrichment technique is capable of producing HEU in just a few stages. Metz (1976) estimated that laser methods could potentially save as much as half the cost and 90 percent of the energy used in GDPs. If the technology is realized, laser methods will enable proliferators to build bombs in their basements.

8.6.2. Molecular Laser Isotope Separation (MLIS)

A. Operation Process

Figure 8.7 and Table 8.9 show the overall schematic and process of MLIS, respectively. For the enrichment operation using MLIS, UF_6 must be supercooled before it is irradiated by lasers, because at room temperature, the collisions between UF_6 molecules are so violent that virtually all of the molecules become excited so that they are above their lowest vibrational states.

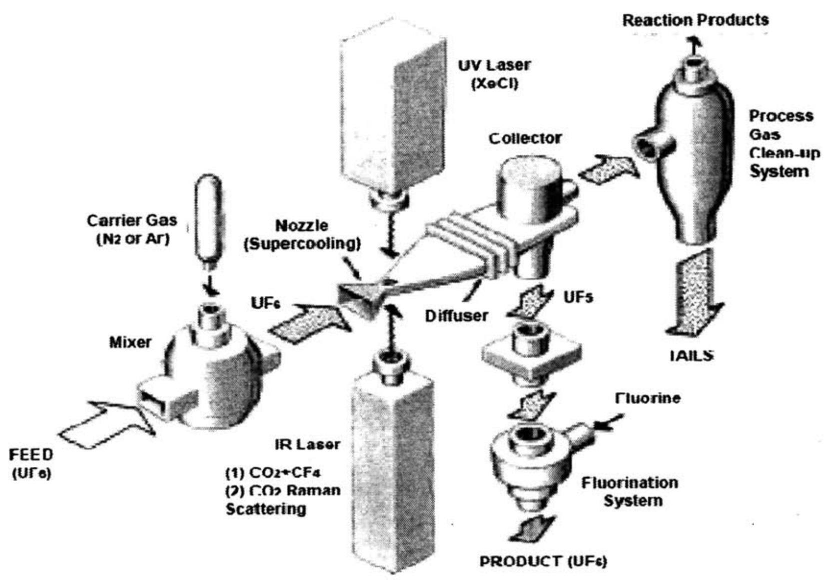

Figure 8.7 Schematic of MLIS

Molecules with a wide range of vibrational energies make it difficult to get any significant selectivity by tuning to a particular vibrational transition. Supercooling the UF6 can solve this problem. MLIS can use either multiple infra-red (IR) lasers or a combination of IR ultraviolet (UV) lasers for the excitation and dissociation of $^{235}UF_6$ molecules. An IR laser should be tuned precisely to selectively vibrate $^{235}UF_6$

because $^{235}UF_6$ and $^{238}UF_6$ have different excitation reactions to infrared laser systems, resulting from the difference in vibration frequencies of the molecules. However, it is extremely difficult to design an optical system that can deal with both IR and UV light. The product of MLIS is $^{235}UF_5$ and is not subject to $^{235}UF_6$ degradation because any non-irradiated $^{235}UF_6$ gas simply continues on to the tails stream.[426] In particular, the higher $^{235}UF_6$ enrichment ratio, the fewer fluorine-exchange reactions are going to occur. However, as the concentration of $^{238}UF_6$ increases, the exchange reaction, which is the cause of $^{235}UF_5$ degradation, will increase and can be represented as follows:

$$^{235}UF_5 + ^{238}UF_6 \leftrightarrow ^{235}UF_6 + ^{238}UF_5 \qquad (8.6)$$

However, the MLIS technology is a stage-wise process and each stage requires conversion of the enriched UF_5 product back to UF_6 for further enrichment, so called **re-fluorination process** as follows:

$$^{235}UF_5 + F \rightarrow ^{235}UF_6 \qquad (8.7)$$

Table 8.9 Process of MLIS[427]

Step		Description
1	Mixing of feed and carrier gas	**Why? Maintain dilute $^{235}UF_6$ density** $^{235}UF_6$ density can easily be made independent of feed assay and thereby always matched to the capabilities of lasers. **What is done?: Prepare for expanding UF_6 in a nozzle** The UF_6 feed and the inert carrier gases such as argon or nitrogen are mixed in the mixer. An inert carrier gas will play a role in expanding the UF_6 through a nozzle.
2	Nozzle	**Why? Put UF_6 molecules in the ground state** In order to use only one single isotopically selective laser for exciting UF_6 molecules, UF_6 molecules must be put into the lowest vibrational state through supercooling. **What is done? Expand and subsequently supercool UF_6** Mixed gas is expanded at supersonic speeds through a nozzle. (UF_6 in a supersonic gas jet. As a result, 95 percent of the molecules are in the vibrational ground state.

[426] For more information about degradation of the product, see Alexander Obermayer, "Uranium Isotope Separation Process Following the Molecular Laser Process," (Fed. Rep. of Germany: Uranit GmbH, 1990).
[427] Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation.*,p.21;Allan S. Krass, "Laser Enrichment of Uranium: The Proliferation Connection," *Science* 196, no. 4291 (1977).; and, U.S. Department of Defense, "Militarily Critical Technologies List (MCTL), Part II: Weapons of Mass Destruction Technologies, Section 5-Nuclear Weapons Technology." p. II-5-17

(Continued)

3	First IR laser radiation	**Why? Selective excite $^{235}UF_6$** In order to excite only $^{235}UF_6$ to its first vibrational state while leaving U-238 UF6 molecules unexcited. **What is done? Irradiate mixed gas with IR laser** An isotopically selective IR laser system operates near the 16 μm wavelength.[428] (i) Option 1: A combination of CO_2 and CF_4 laser system with 16 μm wavelength (ii) Option 2: Raman scattering in hydrogen to step up the wavelength of CO_2 laser light from 10 to 16 μm
4	Second laser radiation	**Why? Molecular dissociation** In order to *dissociate* the excited $^{235}UF_6$ and to *form* $^{235}UF_5$ and free fluorine atoms. **What is done? Molecular dissociation** (i) Option 1 (Multi-step IR multiphoton absorption) (ii) Option 2 (Two-step IR and UV dissociation)
5	Filtering and Re-fluorination	The ^{235}**UF**$_5$ so-called "laser snow" formed from the dissociation precipitates from the gas as a powder that can be filtered from the gas stream and sent on to be *refluorinated* back to UF_6.[429]
	Process gas clean-up	•The remaining gas is cleaned up and sent on for further tails stripping. •A ***scavenger gas*** such as methane is used to capture the fluorine atoms that are released as a result of the dissociation of $^{235}UF_6$ molecules.

B. Proliferation Risk

Krass et al., (1983) expected that MLIS would be the most proliferation-prone process among all available techniques, though it had not been fully developed. However, because of the technical complexity of laser enrichment techniques, it was expected that laser techniques would not be available in the foreseeable future.[430] The separation factor for MLIS, if developed, will be extremely high. Moreover, if coupled with the compact size of a separating element, both inventory and equilibrium time would be reduced. With MLIS technology, there exists no problem in producing weapon-grade uranium at the small warehouse size of an MLIS facility. [431]

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428 Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation.*, p.167. Only one laser is needed to excite most of the $^{235}UF_6$because roughly 95 percent of the UF_6 molecules can be put into the lowest vibrational state, while AVLIS requires four lasers because only a minority of the uranium atoms can be excited out of the lowest energy state.

429 Krass, "Laser Enrichment of Uranium: The Proliferation Connection." mentions that the high ***recombination rates of dissociated molecules (UF_5 and F)*** may ultimately impose a more severe limitation.

430 Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation.* , p.25.

431 Ibid., p.21.

Okamoto and Nishimura (1997) propose three advantages of using MLIS over other technologies:[432]

- The MLIS has a larger separation factor and much shorter holding time. Therefore, it has a much higher diversion probability.
- UF_5 fine particles are likely to be absorbed on the inside wall of a multi-jet impactor, so that they might be accounted as an uncertainty associated with MUF in a collection process.
- Special care should be given to depleted uranium stored on the site. It is easily reusable as feed material.

8.6.3. Atomic Vapor Laser Isotope Separation (AVLIS)

A. History

JNAI's project on AVLIS started in the early 1970s and continued until 1981. In the same year, US DOE decided to direct most of its support to LLNL, which had been doing a similar project since 1972. US DOE estimated that the AVLIS process at LLNL had an advantage over its two competitors, the MLIS process also at LANL and a Plasma process at TRW Corporation. The AVLIS process was the only advanced enrichment method brought to the pilot plant stage in the USA. In 1985, LLNL transferred the technology to United States Enrichment Corporation (USEC) which operated at the former K-25 site. [433] In 1995 USEC and DOE reached an agreement on the transfer of intellectual and physical property of AVLIS technology to USEC. In June 1999, USEC announced that it was discontinuing its development of the AVLIS process. However, research on AVLIS was continued by a private company in Australia.

B. AVLIS Process

AVLIS works on the principle of photo-ionization using a powerful laser to ionize U-235 atoms present in a vapor of uranium metal.[434] AVLIS utilizes very small shifts in the frequencies at which atoms absorb light. Thus, AVLIS requires a laser system that can selectively use light to distinguish tiny frequency shifts because these changes are very small. Figure 8.8 shows the schematic of AVLIS.

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[432] Tsuyoshi Okamoto and Hideo Nishimura, "Uniqueness of Diversion Paths at Molecular Laser Isotope Separation Facility " *Proceedings of the School of Engineering, Tokai University* 23 (1997)..

[433] The U.S. DOE announced the selection of AVLIS as the technology to meet future U.S. needs for the internationally competitive production of uranium separative work. J.A. Paisner, "Atomic Vapor Laser Isotope Separation," *Applied Physics B: Lasers and Optics* 46, no. 3 (July 1988)., pp.253-260.

[434] *Uranium Enrichment* (World Nuclear Association, 2009 [cited 2009 Aug. 13]); available from http://world-nuclear.org/info/default.aspx?id=452&terms=uranium+enrichment.

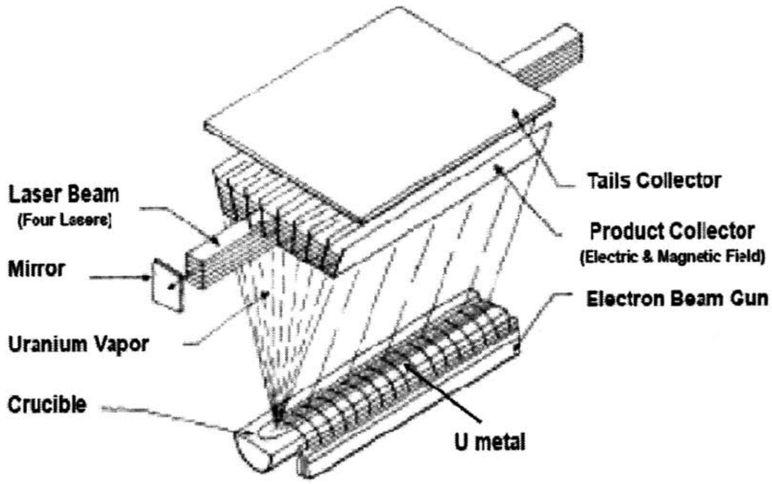

Figure 8.8 Schematic Drawing of AVLIS[435]

The AVLIS process can be divided into three stages. First, the pure metallic form of the uranium ingot is melted into uranium vapor (evaporated atoms at about 2500 °K) [436] in a crucible as shown at the bottom of the figure. An electron-vacuum evaporation unit produces an atomic vapor of natural uranium by heating it with a beam of electrons directed to the surface of the ingot by a magnetic field. An elaborate mechanism must be used to get as many uranium atoms as possible into their lowest energy states and to allow the ionization of atoms by the electron beam to recombine into neutral form. Then vapor moves toward the interaction zone for photoionization.

Second, at the irradiation zone, the U-235 atoms are excited and ionized by four types of dye lasers.[437] As the U-235 atom absorbs the laser light, its electrons are excited to a higher energy state. U-235 atom will become a positively charged ion by ejecting an electron upon the absorption of sufficient energy. The photoionization of uranium vapor takes place when it is excited to the energy level of 6.19 electron volt (eV) via a three-step excitation process as shown in Figure 8.9. Removing an electron from a uranium atom with a total energy of 6.19 eV is very difficult to achieve with a single dye laser in practice in an isotopically selective way because there are three discrete energy levels between the ground state and 6.19 eV. A dye laser system can produce light beams to excite U-235 atoms selectively in a uranium isotope mixture, which is pumped by another high-power system of copper-vapor lasers.

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[435] The size of AVLIS is 1 meter in height and 1-3 meters in length and it is composed of laser system and separation system: a vaporizer and a collector.
[436] The melting point of pure uranium metal is 1,132 °C and the boiling point of liquid uranium is 3,818 °C.
[437] Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation.*, pp.160-166. The rhodamine ***dye lasers*** can be tuned to provide precise laser beam frequency, timing and control in a manner that only the U-235 atoms absorb the laser light. Four lasers of slightly different colors are used, to remove an electron from a uranium atom through isotopical selection. The laser light is being reflected several times through each collection volume by a system of mirrors.

The dye lasers in the red spectral range (590-600 *nm*) are typically chosen to allow transitions between three steps for effective cascade excitation.

Finally, electrically-charged U-235 will become trapped in an electromagnetic field and drawn to a metal plate for collection.[438] The positively-charged U-235 ions are deflected by a pulse of strong electric and magnetic fields and collected on the vertical plates (product collector). Ionized atoms can be separated from the neutral atoms in the beam by the use of electric or magnetic fields. The neutral U-238 atoms continue outward (pass through the product collector) and are deposited on the horizontal plate (tails collector) at the top.

8.6.4. Comparison between MLIS and AVLIS

Both MLIS and AVLIS have excellent features for nuclear proliferation, including a high separation factor, low energy consumption (approximately the same as the centrifuge process), and a small volume of generated waste. But the success of laser enrichment technology is mainly dependent upon the development of suitable lasers. The main differences are that MLIS is a process based on the exchange of resonant vibrational energy in molecules, while AVLIS is a process of atoms and the exchange of ionic charge in atoms between ionized U-235 atoms and neutral U-238 atoms. As a result, three differences between MLIS and AVLIS arise and they will result in different features as follows:

- Different forms of uranium in process: size of facilities, ease of handling, specific requirement for lasers, density restrictions and throughput limitations,
- Use of different laser systems, and
- Different forms of tails assay: collection system requirement, reflux problems, and product degradation.

As for laser systems, both technologies require a laser that can provide isotopically selective light and be precisely tuned to excite UF_6 atoms or molecules. However, the second laser of AVLIS requires a high pulse repetition rate, while MLIS needs a laser with considerably high power to excite large numbers of UF_6 molecules as shown in Figure 8.9

[438] P.A. Bokhan et al., *Laser Isotope Separation in Atomic Vapor* (Weinheim, Germany: WILEY-VCH, 2006).; and Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation*.

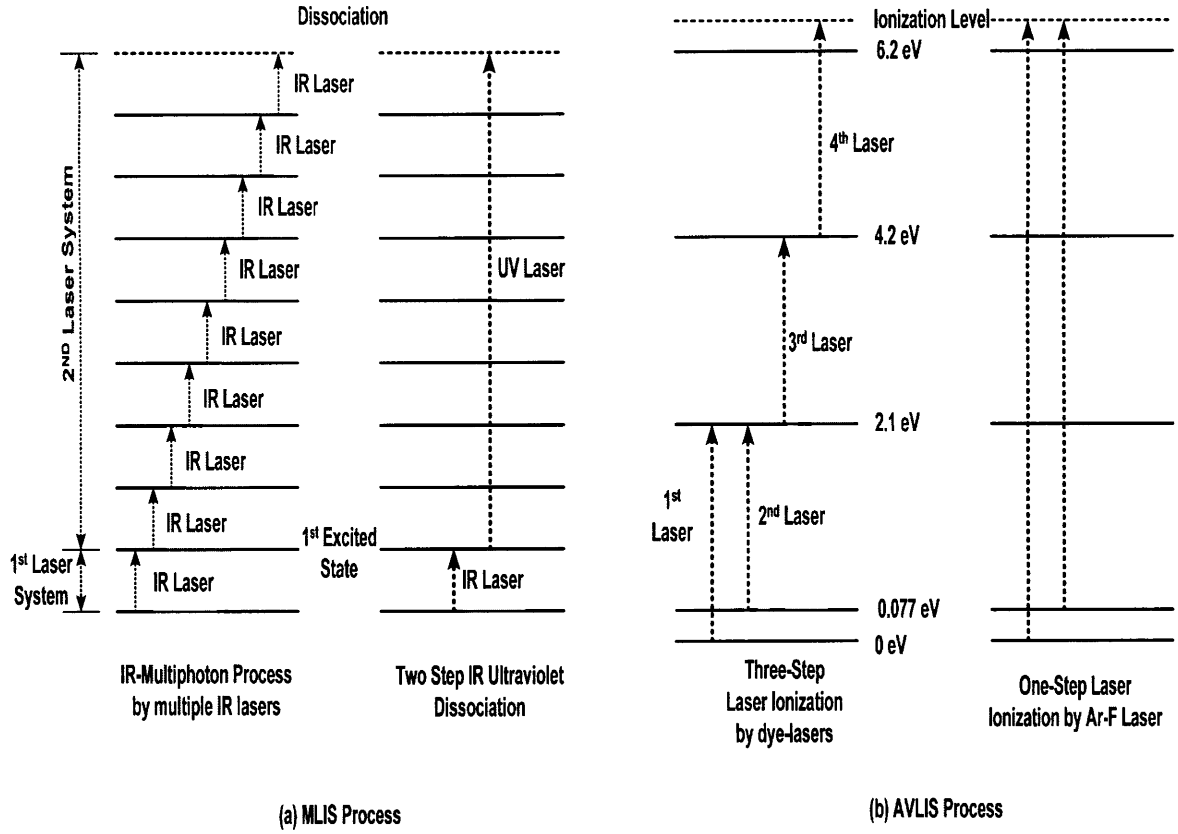

Figure 8.9 Summary of Laser Systems used in MLIS and AVLIS [Krass et al. (1983)][439]

A. Proponents of MLIS

Krass et al. (1983) argue that MLIS is generally regarded as advantageous over AVLIS because the actual implementation of the AVLIS process is likely to be more difficult and expensive than MLIS. AVLIS requires much sophisticated hardware constructed of specialized materials that must be capable of reliable operation for extended periods of time in a harsh environment.

First, MLIS is better in the handling of feeds, tails and products. MLIS uses UF_6 and produces enriched product in the form of UF_5. In contrast, AVLIS uses a metallic form of uranium as feed and then proceeds to the atomic vapor. The atomic vapor is very hard to handle because if its high temperature and corrosiveness. The molecular process of MLIS can be conveniently operated in stages because enriched product in the form of UF_5 can be filtered from the gaseous tails stream. In addition, non-irradiated UF_6 gas at MLIS can be easily dealt with because it simply continues on into the tails stream and has no effect on the product assay of the irradiated vapor. The formation of "***UF_5 snow***" facilitates the segregation of the product from tails and removes the need for very high laser pulse rates, which are required in the AVLIS process. In the case of AVLIS, non-irradiated vapor is collected at a

[439] Figure 6.19 on page162 and Figure 6.22 on page 169.

fixed rate along with the irradiated U-235 ions. The need to collect and recycle large quantities of uranium, which condense out of vapor would create a significant reflux problem.[440]

Second, MLIS may be capable of considerably higher production rates than AVLIS for a given interaction volume because AVLIS uses uranium vapor of very low density to enrich uranium. An MLIS facility is going to be much smaller than an AVLIS facility for the same enrichment capacity because of two factors: the atomic vapor used in AVLIS is much less dense than the gaseous UF6 used in the molecular process, and MLIS has a less complex optical system for the laser beams because much smaller irradiation volumes are required than for AVLIS.

Third, the MLIS has a higher operational efficiency than AVLIS. Only 50 percent of the evaporated atoms reach the irradiation zone and the rest are deposited on various surfaces inside the chamber. About 70 percent of the uranium atoms reached and placed in the zone are illuminated by the lasers and another 30 percent goes on to the tails collector as neutral particles. Configuration of cascades at MLIS facility is easier than that of AVLIS because the enrichment efficiency of MLIS would further improve at higher assays.

Fourth, MLIS is better suited to produce HEU than AVLIS. The higher the feed assays at MLIS, the less degradation of product would occur as a result of fluorine-exchange reactions. However, as for AVLIS, vapor state requires a collector unit of large size for a HEU production and the issue of ***plasma shielding effect*** becomes problematic as U-235 enrichment rates go up.

B. Proponents of AVLIS

Metz (1976) and the U.S. DOE prefer AVLIS over MLIS. They argue that MLIS seemed to be a great gamble. This view is in the opposition to Krass et al., (1983). The advantage of AVLIS could be two factors. First, its high selectivity could lead to one-pass enrichment with low tails assay with the result of lower quantities of uranium being used. Theoretically, three batch recycles makes it possible to produce 97 % HEU from natural uranium. Second, the required laser power for AVLIS is not as great as that for molecular processes, although the pulse repetition rate (the number of emitted pulses per second) must be higher to obtain reasonable production rates.

In contrast, Metz (1976) pointed out two critical weaknesses of MLIS: difficulty with finding the wavelength that could selectively excite $^{235}UF_6$ because of high density of the molecules; and the great power requirement for the second laser system. MLIS cannot be used in enrichment of Pu metal while such is possible with AVLIS. These factors might have contributed to the development of SILEX, which is an advanced version of AVLIS rather than MLIS. [441] Table 8.10 shows a comparison of key features between MLIS and AVLIS.

[440] Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation.*, p.162.
[441] Paragraph 114. "INFCIRC/640, Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report Submitted to the Director General of the IAEA."

Table 8.10 Comparison of Key Features between MLIS and AVLIS [Krass et al., (1983)]

Specifications	MLIS	AVLIS	Preferred Option for Proliferation
Irradiation volume	Smaller	Larger	MLIS
Handling of Uranium	UF_6	Uranium vapor	MLIS
Process operation	Convenient (molecules)	Complicated (atoms)	MLIS
Degradation of product	Less	More	MLIS
Specific Size of facility	Smaller	Larger	MLIS
Collection system	Not required	Required	MLIS
Overall efficiency	lower	higher	AVLIS
Power requirement	Higher	Lower	AVLIS
Applicability to Pu	No	Yes	AVLIS

8.6.5. SILEX – Advanced AVLIS Technology

A private Australian company (Silex technology) operating out of the Australian Nuclear Science and Technology Organization (ANSTO) facility has successfully developed a new laser enrichment technology called "SILEX (Separation of Isotopes by Laser Excitation)", with support from the US Enrichment Corporation from 1996 to 2002. In 2001, the Silex process was officially classified by the US Secretary of Energy and the Australian government. On 22 June 2006, Silex Systems announced US government approval for an agreement giving exclusive commercialization rights to General Electric Company. The Silex-GE agreement resulted in commercial deployment of laser enrichment in the US. In 2007, the Silex Technology licensed the SILEX process to General Electric.

The process is based on selective excitation of uranium hexafluoride (UF6) molecules that contain U-235 by laser light at a narrow spectral line near 16 μm, but few details have been released. Many details are classified or proprietary.

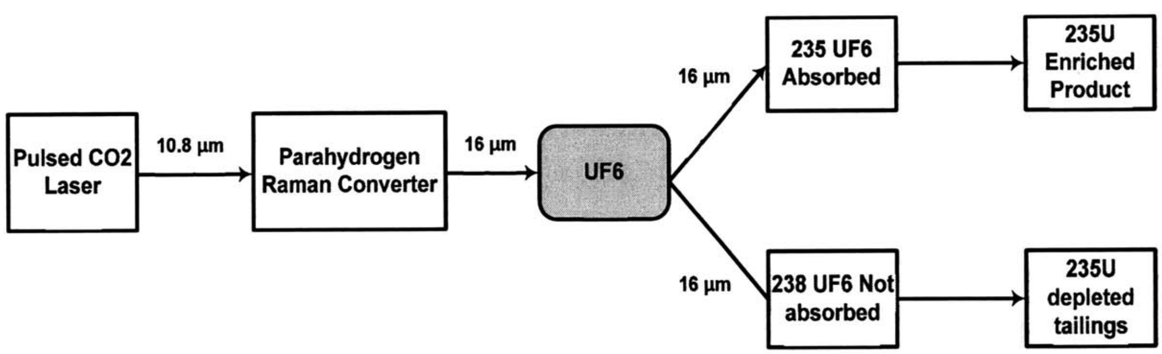

Figure 8.10 Simple Schematic of Silex Technology Process[442]

[442] In the Silex process, light at 10.8 μm from a CO_2 laser is converted to a 16 μm wavelength and used to separate U-235 from U-238. Beljac, *Pakistan and the Prospects for Nuclear Terrorism*.

As shown in Figure 8.10, the pulsed CO_2 lasers can generate pulses, but with limited efficiency and limited repetition rate. To convert the CO_2 laser of 10.8 μm to 16 μm, a Parahydrogen Raman converter is needed as a nonlinear optical trick. As far as production rate is concerned, it would take about 100 hours to produce one kilogram of U-235, assuming complete separation of U-235 and U-238 isotopes, if a laser could illuminate a one-liter volume at an ideal repetition rate.

Nonproliferation issues can be very significant if this new laser enrichment technology is commercialized. A Greenpeace report on the Silex project at ANSTO quotes a 1981 declassified CIA report on threats posed by laser enrichment of uranium: "Any country might acquire the necessary technology to set up a garage sized plant to produce weapons grade uranium anywhere in the world". In addition to the generally favorable features of laser enrichment technology, SILEX is expected to lower capital costs and produce considerably fewer greenhouse gas emissions. Furthermore, relatively simple and practical separation modules and modular technology will provide versatility in deployment. However, the current level of SILEX technology does not appear mature enough to enrich U-235 concentration to the higher levels needed for nuclear weapons, according to a researcher who reviewed the SILEX process for the International Atomic Energy Agency (IAEA).[443]

8.7 Gaseous Diffusion Technology

The world's first commercial uranium enrichment facility was the Portsmouth plant. It used gaseous diffusion technology in mid-1960s and shifted from a military mission to a commercial focus.[444] At present the gaseous diffusion process accounts for about 40% of world enrichment capacity. This technology has proved durable and reliable. However, most Gaseous Diffusion Plants (GDPs) are now nearing the end of their design life. GDPs are being phased out as newer gas centrifuge enrichment plants are constructed. The GDP is composed of a series of diffusion stages and each stage consists of a compressor, a diffuser, and a heat exchanger to remove the heat of compression. More than a thousand stages must be linked for enrichment operation.

[443]Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation*., p.166. This is due to a plasma shielding effect. Tuning the lasers to excite U-238 will work only if the plasma shielding effects remain small, up to 50 percent ionization. If the U-235 content is over 50 percent, the lasers can be tuned to remove U-238 instead. If laser powers are increased, then the U-235 plasma created by the ionization becomes so dense that the efficiency of the ion collectors drops.

[444] USEC, *History: Portsmouth Gaseous Diffusion Plant* ([cited Jan.1 2009]); available from http://www.usec.com/gaseousdiffusion_ports_history.htm.

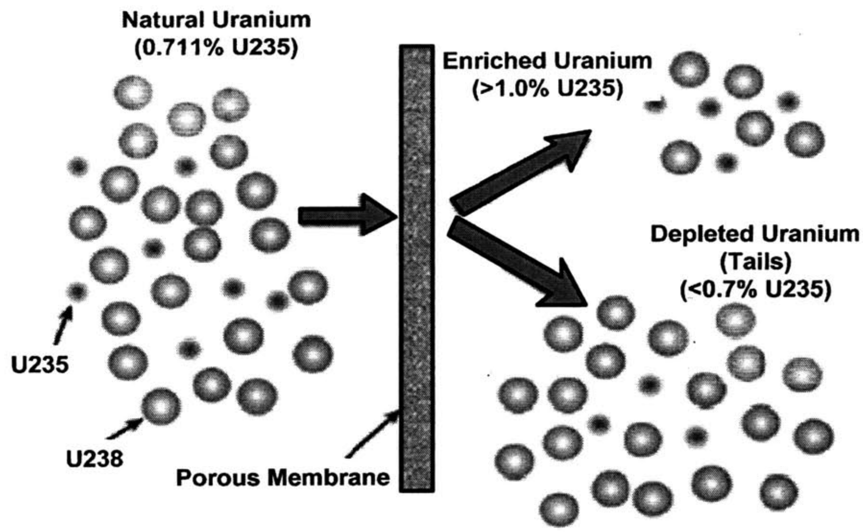

Figure 8.11 Gaseous Diffusion Process [U.S. NRC][445]

The basic physical principle underlying the gaseous diffusion technique is the so-called '***equipartition principle***' of statistical mechanics. This principle states that in a gas consisting of several types of molecules each type will have the same average energy of motion (kinetic energy)[446]. If two particles have the same kinetic energy, the one with the smaller mass will have the larger velocity. In the gaseous diffusion process this velocity difference is exploited by allowing the gas to diffuse through a solid barrier permeated by many small holes or pores (i.e., through the preferential permeability of U-235 through a porous membrane). The faster-moving molecules, which are U-235 atoms, pass through the holes more frequently, and the mixture which emerges on the other side of the barrier is therefore somewhat richer in the light species than the original sample. This process is repeated many times in a cascade.

A typical GDP covers a large floor space and consumes enormous quantities of electrical power for its pumps and compressors. The old GDPs use hundreds or thousands of large compressors; hence they require approximately 10,000 W/m^2.[447] The gaseous diffusion technique requires more than 1400 stages to produce LEU, a lot of energy, a large amount of in-process uranium, and a long time to reach equilibrium.

8.8 Other Uranium Enrichment Technologies

Aerodynamic separation, plasma separation, chemical separation, and electro-magnetic isotope separation (EMIS) are other possible techniques for enriching uranium. The EMIS process was the only electromagnetic processes practically developed in the early 1940s in the Manhattan project to make

[445] U.S. Nuclear Regularatory Commission, "Gaseous Diffusion Uranium Enrichment Process," (2007).
[446] Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation.*, p.121.
[447] Laughter, "Profile of World Uranium Enrichment Programs - 2007, ORNL/TM-2007/193."

HEU. However, it was abandoned soon afterwards. It reappeared as the main thrust of Iraq's clandestine uranium enrichment program for weapons discovered in 1992. All electromagnetic processes use magnetic fields to accelerate uranium ions. If an atom or molecule can be ionized, it can then be accelerated by either electric or magnetic fields or both. EMIS is very energy-intensive and consumes about ten times as much energy as gaseous diffusion. Sometimes, plasma separation is classified as EMIS; however, it uses the principle of ion cyclotron resonance to selectively energize the U-235 isotope in a plasma state.

The chemical-exchange process utilizes the very small tendency of different isotopes of an element to concentrate in different molecules when there is an opportunity for exchange between molecules. Only Japan and France developed chemical exchange processes, the Asahi Chemical Exchange Process and the French Chemex process. Chemical-exchange processes involve a long equilibrium time and facilities of large size. In addition, the separation effect decreases as isotopic mass increases.

Aerodynamic separation technique refers to two methods: the separation nozzle process and the vortex tube separation process. The separation nozzle process was developed by E. W. Becker at the Karlsruhe Nuclear Research Center in Germany and the vortex tube separation process was developed in South Africa, which is also called the Helikon process named after a cascade design technique, called Helikon. This process creates centrifugal forces by forcing a mixture of UF_6 gas and either hydrogen or helium through a nozzle at high velocity and then over a curved surface.

8.9 Comparison of Uranium Enrichment Technologies

There have been a number of attempts to evaluate the proliferation sensitivity of various enrichment techniques. It is not easy to develop a single straightforward and quantitative index. Krass et al., (1983) used five indices to rate the proliferation dangers of enrichment techniques. Table 8.11 compares each uranium enrichment technology in relation to proliferation risks. Each index is set on a three-point scale, ranging from low (1) to high (3). These have to be conceived as relative terms. Laser-based uranium enrichment facilities, if commercialized, pose the highest threat to the current nonproliferation regime. High separation values imply that fewer stages are required. Based on Table 8.11, gaseous diffusion, gas centrifuge, and laser enrichment technology need particular attention with regard to nuclear proliferation.

Table 8.11 Summary of Enrichment Process Characteristics [Krass et al., (1983)]

Process		Working matrix	Separation factor	Specific energy consumption (kWh / SWU)	Required number of stages for HEU	Equilibrium time
Gaseous diffusion		UF_6	1.0040-1.0045	2300-3000	3500-4000	Months
Gas centrifuge		UF_6	1.3-1.6	100-300	<60	Hours
Electromagnetic	**Calutron**	UCl_4	20-40	3000-4000	2	5-15 days
	Ion cyclotron	U plasma	3.5-10	200-600	N/A	
Aerodynamic	**Nozzle**	UF_6	1.015	3000-3500	2500-3000	Days
	Helicon (Vortex tube)		1.025-1.003		Thousands	
Chemical	**Solvent extraction**	Aqueous uranium solution	1.0025-1.003	<600	5000-6000	>150 days
	Ion exchange		1.0013	400-700		
Laser	**MLIS**	UF_6	5-15	10-50	<4	Very short
	AVLIS	U vapor	5-15	10-50[448]	<4	

Source: Required number of stages and equilibrium time from The Safeguards Options Study (1995), Table 7-II, p.91.

[448] Lenders, "Uranium Enrichment by Gaseous Centrifuge". assumes MLIS (40) AVLIS (150).

Table 8.12 shows a more detailed analysis for the three technologies suggested by Krass et al. (1983). As discussed earlier, gaseous diffusion is far from being useful for nuclear proliferation. On the contrary, gas centrifuge and laser enrichment technology can be well-suited for nuclear proliferation. However, laser enrichment technology is yet to be developed for commercialization.

Table 8.12 Enrichment Technique Property Ratings and Proliferation Threshold [449]

Technology		Separation factor	Equilibrium time and inventory[450]	Facility size	Ease of batch recycle	Proliferation threshold*	
						Misuse of existing facility	Construction of dedicated facility
Gaseous Diffusion		Low	Low	Low	Low	Medium	High
Gas Centrifuge		Medium	High	High	High	***Low***	***Intermediate***
Laser	***MLIS***	High	High	High	High	***Low***	***Intermediate***
	AVLIS	High	High	Medium	Low	Intermediate	High

Note: High threshold means it is relatively difficult to use the facility for proliferation purposes.

8.10 Summary

The various uranium enrichment technologies have been reviewed in association with possible proliferation risks. A uranium-based nuclear weapons program was chosen for the scope of study because it provides an edge over a plutonium-based program from several aspects. Among the currently available uranium enrichment technologies, gas centrifuging poses the most challenging threat for the nuclear nonproliferation regime. The gas centrifuge has good features suited for nuclear proliferation. Also, gas centrifuging is increasing its shared total world capacity and it replaced gaseous diffusion, which was the first generation commercial technology. Though laser enrichment technology is about a decade away from commercial use, it may pose an alarming threat to international security once it reaches the level of commercialization. For now, gas centrifuge technology is the technology that requires a particular attention with regard to nuclear proliferation. Among available technologies, only gaseous diffusion and gas centrifuge have reached the level of commercialization, and gas centrifuge technology can operate much more efficiently than gaseous diffusion technology. In addition, laser enrichment technology is expected to impose serious security threats once it is available on a commercial scale.

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[449] Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation.*, Table 2.1 on p.19 and Table 2.2 on p.26.

[450] Sharikov, "Verification Challenges for Safeguarding Uranium Enrichment Plants."The inventory hold-up in a typical cascade is a few kg for a GCEP and a thousand metric tons for a GDP. The equilibrium time for a typical cascade is on the order of minutes to tens of minutes and weeks to months for a GDP. It is suggested that 5 kg of uranium is required to fill a 10,000 SWU/year cascade , E.A. Hakkila et al., *The Safeguards Options Study.*, p.90.

CHAPTER 9
TECHNICAL SPECIFICATION OF GAS CENTRIFUGE ENRIHMENT PLANTS AND NUCLEAR PROLIFERATION

9.1 Introduction

The purpose of this chapter is to review why Gas Centrifuge Enrichment Plants (GCEPs) are important in dealing with nuclear nonproliferation issues from a technical point of view. At present, Gas Centrifuge Enrichment Technology (GCET) is the most efficient enrichment technology, and it is well-suited for nuclear proliferation. GCET is not only very efficient and economic in enriching uranium but flexible in diverting LEU-producing facilities to HEU-producing facilities. In this regard, understanding the technical specifications of GCET is essential to analyze a proliferator's possible proliferation activities.

There have been publications that provide detailed explanations about GCET.[451] However, most of them are not easily understood by readers who have general interest in GCET for nuclear non-proliferation issues. It is because those publications describe GCET from a technical perspective. In addition, they do not deal with contemporary GCET-related issues because most of them were published between the early 1950s and the early 1980s. However, GCET has since the early 1980s and its use by Pakistan has raised the issue of using GCET for proliferation. In this regard, there exists a need to provide a balanced description about GCET from both technical and nonproliferation perspectives.

This chapter will give insights into nonproliferation issues with regard to GCEPs such as what kinds of technologies are required for a proliferator to build GCEPs and how GCEPs can be diverted to produce HEU for nuclear weapons. This chapter begins by reviewing fundamental theories of GCET, ranging from the design of a gas centrifuge machine to a cascade formation. And then ways to divert GCEPs producing LEU to GCEPs producing HEU are reviewed, coupled with some of the technical challenges in doing so. This chapter concludes by reviewing the evolution of the gas centrifuge technology and the potential use of GCEPs for nuclear proliferation.

9.2 Separation Theory of Gas Centrifuge

9.2.1 Basic Principles

The forces work in gas centrifuge machines can be classified as vertical and horizontal ones. Axially, all particles in a gas centrifuge machine are under the influence of gravity. The density distribution of two different isotopes along the axis can be written as:

[451] Cohen, *The Theory of Isotope Separation as Applied to the Large Scale Production of U-235.*; D.G. Avery and E. Davies, *Uranium Enrichment by Gas Centrifuge, Isotope Separation* (London, U.K.: Mills & Boon Ltd., 1973).; Villani, *Isotope Separation.*; and Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation.*

$$\frac{N_{U235}(h)/N_{U235}(0)}{N_{U238}(h)/N_{U238}(0)} = \frac{R(h)}{R(0)} = \exp[-(m_{U235} - m_{U238})(\frac{gh}{RT})] \qquad (9.1)$$

where N is the density of particles, R is the relative isotopic concentration ratio, T is absolute temperature, g is gravity, h is the height, and m is the molecule's mass. [452]

Radially, a rapidly rotating centrifuge generates the force from "centrifugal acceleration" and this force replaces the force generated by the acceleration of gravity. The distribution of two isotopes can be shown as:

$$\frac{R(r)}{R(0)} = \exp[(m_{U-235} - m_{U-238})\frac{r^2\omega^2}{2RT}] \qquad (9.2)$$

where ω is the angular velocity (rad/sec), r is the distance from the center of the centrifuge, m is the molecular mass, T is the absolute temperature, and R is the ideal gas constant.[453]

9.2.2. Actual Modeling of Isotope Separation in a Gas Centrifuge

In reality, the separation of two isotopes in gas centrifuges is far more complex than basic principles. It is very important to have good models of the internal flow of UF_6 gas in a gas centrifuge machine. Such models are needed to seek the optimal operating conditions of the centrifuges based on fluid dynamics and to predict the separation performance for design optimization. The change in the concentration of the U-235 along the axial direction of a rotor in the presence of radial convective flows and the dependence of the axial concentration gradient on the radial direction can be described in the form of differential equations.

In any type of gas centrifuges, none of the local points has the same concentration of U-235. In the radial direction, the U-238 is flung closest to the wall, while the U-235 mostly migrates towards the center. In the vertical direction, a vertical counter-current forms along the rotational axis of the cylinder, and it transforms the radial isotopic gradient into an axial gradient. The current flowing upwards is gradually enriched with U-235 atoms while the downward current is depleted with more U-238 atoms than the feed. Depleted and enriched fractions are caught by scoops at carefully optimized distances from the cylinder wall.

Cohen (1951) developed ***the approximate approach*** based on the stream function to describe the in-rotor flow and derived the one-dimensional equation. ***Onsager's pancake model*** is one of

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[452] Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation*. p.128.
[453] Moody, Hutcheon, and Grant, *Nuclear Forensics Analysis*."α" is used in Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation*., p. 129.

approximated models in two dimensions, which simplifies the system of equations into a single, dimensionless, linear partial differential equation valid in the region away from the ends of the cylinder.[454] However, this approach is not applicable to that is non-uniform circulatory flow resulting from approximations and assumptions in the derivation: uniform flow along the axis, the neglect of the axial diffusion flux, and the allowance of the violation of the boundary conditions for radial diffusion flow.[455]

At present, ***the radial averaging method*** is the main method that simplifies the analytic description of centrifuge separation of isotopes. The radial averaging method is based on the rotational potential and it decomposes the mass flux density inside the rotor into rotational and potential components. This method is applicable to any arbitrary circulatory flux in the rotor.[456]

Table 9.1 Separation Power of Gas Centrifuges

Terms	Description
Separation power	**#1 General description** $\delta U = \int_o \Phi\Delta(N)\frac{d^2V}{dN^2}dO = PV(N_P)+WV(N_W)-FV(N_F)$ Φ is the total diffusion flux, V is the value function which depends only on the molar concentration N. P, W, and F stand for product, waste and feed, respectively.
	#2 Ideal cascade $u = \frac{1}{2}\varepsilon^2 f$ where ε = separation gain and f = the flow rate per centrifuge[457]

(Continued)

[454] H. Wood and J. Morton, "Onsager's Pancake Approximation for the Fluid Dynamics of a Gas Centrifuge," *J. of Fluid Mechanics* 101, no. 1 (1980)., pp. 1-31; W.H.Furry, Clark Jones, and L. Onsager, "On the Theory of Isotope Separation by Thermal Diffusion " *Physical Review* 55, no. 9 (June 1939)., pp.1083-1095. This was named after the late Dr. Lars Onsager, who led a group of scientists to develop a theory of the hydrodynamics of the flow in a gas centrifuge. The work began in 1961.

[455] Aleksandrov, "Comparison of Two Approaches to Using the Averaging Method for Analyzing Separation in a Gas Centrifuge." The description of the mass flux density in a gas centrifuge can be made by the rotational potential-based and the stream function-based derivations. For many reasons, the former method is preferred in the analysis.

[456] Ibid.; V.I. Tokmantsev, "More Accurate Equation for Radial-Averaging Analysis of the Separation of a Binary Isotopic Mixtures in a Gas Centrifuge Radial," *Atomnaya Énergiya* 92, no. 5 (May 2002).; and Aleksandrov, "Comparison of Two Approaches to Using the Averaging Method for Analyzing Separation in a Gas Centrifuge."

[457] Toshio Kawai et al., "Sensitivity Analysis of Ideal Centrifuge Cascade for Producing Slightly Enriched Uranium," *Journal of Nuclear Science and Engineering* 50 (1973)., pp.63-72.

Maximum Separation power	**#1 Dirac's classical expression of maximum separative power** [458] $\delta U_{Dirac,\max} = \frac{\pi}{2}\rho DH[\frac{\Delta m(r\omega)^2}{2RT}]^2$ **#2 Absolute maximum separative power** [459] $\delta U_{abs,\max} = 2\pi\rho DH(\frac{\Delta m(r\omega)^2}{2kT})^2$ H is the height of a rotor, D is the diffusion coefficient, k is Boltzmann's constant, T is the mixture temperature, Δm is the difference of the molecular mass of the components of the mixture, ω is the angular rotational velocity of a rotor, ρ is the density of a mixture, r is the radius.

Note: Kemp calls Dirac's expression the separative performance for a gas centrifuge. [460]

Table 9.1 shows the definition of the separation-related terms that are used in the description of separation principles in a gas centrifuge. Single-stage separation factor is the ratio of isotopic abundances at the center of centrifuge to that near the wall or the relative abundances of the enriched and impoverished separation fractions. Separative power is the rate of change in value produced by the separative element and is measured in the same units as the feed flow [kgSWU per unit time]. Thus, the performance of a gas centrifuge machine is often described using separative power. It should be noted that the maximum separative work is used as a standard to evaluate the efficiency of the various centrifuge designs. From the maximum separation power, it can be concluded that the maximum separation power of the centrifuge is proportional to the fourth power of the peripheral velocity.[461] However, it should be noted that the flow-profile efficiency reduces the fourth power exponents as the peripheral velocity increases. [462]

[458] Cohen, *The Theory of Isotope Separation as Applied to the Large Scale Production of U-235.*, pp. 109-111.
[459] For more discussion see O.E. Aleksandrov, "Separation Power of a Gas Centrifuge and Certain Errors in Optimizing the Centrifuge," *Atomic Energy* 92, no. 3 (Mar. 2002)., pp.230-238. He claims that the Dirac's limit for the separation power cannot be applicable to modern centrifuges due to the limitations of the mass conservation law.
[460] R. Scott Kemp, "Gas Centrifuge Theory and Development: A Review of U.S. Programs," *Science & Global Security* 17, no. 1 (2009).
[461] However, Ratz claims that the maximum separative power is proportional to the second power of the peripheral velocity in case of very fast centrifuges due to the emptying of the interior of the machine, based on his two-shell radii model. E. Rätz, "Analytische Lösungen für die Trennleistung von Gaszentrifugen zur Urananreicherung," Ph.D. Thesis (Technical University of Berlin, 1983) [cited in A. Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapons Proliferation," *Science & Global Security* 16, no. 1 (2008)., pp.1-25.
[462] E. Raetz, "Uranium Isotope Separation in the Gas Centrifuge" (paper presented at the The VKI Lecture Series on Aerodynamic Separation of Gases and Isotopes, Belgium May 29- Jun 3 1978)..Thus, at 313 m/s, the exponent is 4, but at 440 m/s the exponent has dropped to 2.7, and at 750 m/s the exponent has dropped to 2.2.

9.3 Design of a Gas Centrifuge Machine

9.3.1 Classification of Gas Centrifuge Model

A gas centrifuge machine requires very high level technologies ranging from hydrodynamics to computational science. For example, computational models are used to model fluid flow inside the centrifuge based on the ***convective diffusion equation***, with different design factors and varying degrees of simplicity based on assumptions such as boundary layers. A gas centrifuge model has evolved and it is categorized based on the following four factors:

- Material of rotors: Aluminum, maraging steel, or Carbon Fiber Resin Composite (CFRC)
- Criticality of rotor speeds: rotors rotate above or below critical speeds, i.e., supercritical rotors or subcritical rotors
- Number of axial segments: number of tubes connected by bellows
- Internal flow scheme: concurrent flow regime or countercurrent flow regime[463]

Among these, first three factors are associated with the choice of material.

9.3.2 Material Selection

Material problems have been a major constraint on the development of an optimized design for a gas centrifuge machine. The most challenging issue with regard to material is to produce a reliable rotor material because a rotor is spinning at extremely high speeds. Three factors including the tensile strength of the rotor, resonance frequency, and chemical resistance must be considered when a material is chosen for the centrifuge machine. The development of bearings that can endure mechanical stress from ultra-high speed rotation is also important.

A. Tensile Strength of the Rotor

The rotor should be able to resist the centrifugal stress as designers increase the peripheral speed. The tensile stress (σ_{UTS}) of a rotor is given as[464]

$$\sigma_{UTS} = \rho(r\omega)^2 = \rho v^2 \qquad (9.3)$$

where r is the distance from the center of the cylinder to the wall of the cylinder, ρ is the density, ω is the angular velocity, and v is the peripheral speed. Therefore, the maximum speed is given as

[463] Cohen, *The Theory of Isotope Separation as Applied to the Large Scale Production of U-235.*, pp. 114-125
[464] Ibid., p.110.

$$v_{\max} = \sqrt{\frac{\sigma_{UTS}}{\rho}} = \sqrt{\frac{the\, tensile\, strength\, of\, material}{the\, density\, of\, the\, rotor}} \qquad (9.4)$$

The maximum speed of a gas centrifuge can be increased by introducing high strength-to-density (or strength-to-weight ratio) materials for a rotor as shown in Table 9.2. The ratio in the square root is often called the ***specific length***. The rotor will break if T is greater than the tensile strength of the rotor material.[465]

Table 9.2 Typical Maximum Peripheral Speeds of Thin-Walled Cylinders [Whitley (1979)][466]

Material	Tensile strength (σ_{UTS}) [kgf/cm^2][a]	Tensile strength (T) [N/cm^2]	Density (ρ) [g/cm^3]	T/ρ [(m/s)^2]	Approximate max peripheral speed (m/s)
Al alloy	5200	50960	2.8	185,700	425
Titanium	9200	90160	4.6	200,000	440
High-strength steel	17000	166600	8.0	210,000	455
Maraging steel	22500	220500	8.0	281,300	525
Glass fiber/resin	7000	68600	1.9	368,400	600
Carbon fiber/resin	8500	83300	1.7	500,000	700

Note: [a] 1kilogram-force (kgf) =9.8 Newton (N) and the unit of Newton is [kg·m/s^2].

B. Resonance Frequency

The rotation of a long, thin rotor generates characteristic vibrations and flexion that can wreck the rotor or its bearings when the frequency of rotation coincides with the natural frequency of the rotor, such frequencies are called ***transverse*** or ***flexural vibration modes***.[467] The speeds at which these violent

[465] Ibid., p. 110.

[466] Stanley Whitley, "The Uranium Ultracentrifuge: The Story of the Development of the Gas Centrifuge for the Separation of the Isotopes of Uranium," *Physics in Technology* 10 (Jan. 1979).

[467] Ibid.;Agnieszka Muszyǹska, *Rotor Dynamics* (Boca Raton, FL CRC Press, 2005)., p.1048.The state of rotor vibration (rotor mode) can be identified by several characteristics: natural frequency, hierarchy (first, second, third, etc), deflection shape (rigid or flexible), or end-to-end relative phase (in phase or out of phase).

vibrations occur are called critical speeds.[468]In a gas centrifuge, these occur when the speed of a rotor coincides with the natural frequencies of vibration of the non-rotating shaft on its rigid bearings.[469] A natural frequency and a resonance frequency are given by:

- Natural frequency: $f_{natural} = (\frac{1}{2\pi})(\frac{k}{m})^{1/2}$ (9.5)

- Resonance frequency: $f_{resonance} = \frac{nv}{2d}$ (9.6)

where k is the material stiffness, m is the mass of weight, n is an integer number, d is the travel distance of the resonator, and v is the velocity of a wave.

As shown in equations (9.5) and (9.6), the natural frequency ($f_{natural}$) is inversely proportional to the square root of the mass, whereas the resonance frequency ($f_{resonance}$) is inversely proportional to the travel distance. As the length of a rotor increases, the travel distance and the weight of material will increase. This implies that the vulnerability of a rotor to the resonance occurrence increases as a designer achieves the higher separation efficiency by increasing the length of the rotor. To avoid critical speeds from occurring during operation, a rotor must spin below or above its critical speed (i.e., subcritical or supercritical, respectively). Supercritical operation naturally involves greater difficulties than does subcritical as shown in Table 9.3. The longer the rotor or more specifically, the higher the length-to-diameter ratio, the higher the number of critical speeds which must be negotiated during acceleration.[470]

Table 9.3 Length-Diameter Ratio (L/D) and Corresponding Critical Speeds of Aluminum Rotors [Whitely (1979)]

L/D	**Critical speeds (m/sec)**				**Number of critical to negotiate if a rotor spins at 350 m/sec**
	1st	**2nd**	**3rd**	**4th**	
7	400				0
11.6	145	400			1
16.3	74	204	400		2
21	45	123	242	400	3
25.5	30	83	162	269	4

[468] Critical speeds can be defined in several ways: (1) The critical speed is the theoretical angular velocity which excites the natural frequency of a rotating object or (2) The speed at which the frequency of rotation coincides with natural frequencies. Critical speeds can be translated in terms of '**critical rotation frequencies.**'
[469] Den Hartog, *Mechanical Vibrations* (York, PA: The Maple Press Co., 1947)., p.285.
[470] Whitley, "The Uranium Ultracentrifuge: The Story of the Development of the Gas Centrifuge for the Separation of the Isotopes of Uranium."

The issue of critical speeds can be solved through damping vibrations as well as developing a centrifuge that can endure mechanical stresses when accelerated through the critical speeds. Two approaches are available to get around this problem for supercritical rotors. First, the use of multiple bellows and tubes will allow a gas centrifuge to avoid resonance destruction by having multiple axial segments, which allows controlled flexing. Tubes are connected with bellows in a gas centrifuge machine.[471] Second, the use of a lighter rotor material can help overcome the problem by increasing the natural frequency of the rotor. The use of a light material can increase not only the natural frequency but also the resonance frequency because, in many cases, the natural frequency and the resonance frequency are almost equal to each other when damping[472] is very small. This will result in lower probabilities of the generation of destructive vibration.

C. Chemical Resistance

The rotor must be able to resist a high chemical reactivity of UF_6 in addition to endure mechanical stress. UF_6 reacts vigorously with water and several metals, but Ni, Cu, and Al are resistant. However, the presence of even small quantities of hydrogen fluoride (HF), one of by-products of UF_6 hydrolysis, increases the rate of attack on even the resistant metals. [473] Hydrofluoric acid, a solution of hydrogen fluoride in water, attacks glass, concrete, and many metals. It also attacks carbonaceous natural materials such as wood derivatives, leather, and rubber. Some materials resist the corrosive action of the acid, such as platinum, wax, polypropylene, polyethylene, and Teflon. In contact with metals with which it will react, hydrogen gas is liberated and the danger exists of a spark or flame resulting in an explosion.[474]

9.3.3 Types of Centrifuges

Gas centrifuge design can be classified as evaporative (or vacuum-type air-driven), concurrent, or countercurrent (or Urey scheme). Modern centrifuges use a countercurrent flow design because the countercurrent flow can generate an internal reflux that results in a recirculation of gas in the machine. These three types of centrifuges are shown schematically in Figure 9.1.

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[471] Marvin Miller, "Appendix I the Gas Centrifuge and Nuclear Proliferation," in *A Fresh Examination of the Proliferation Dangers of Light Water Reactors*, ed. V. Gilliinsky et al. (The Nonproliferation Education Center, 2004). A very careful control of the rotation speed by connecting a number of shorter rotor segments with flexible bellows to ensure that the centrifuge does not operate for very long at speeds where resonance is a problem.

[472] Muszyǹska, *Rotor Dynamics* p.90. Damping is the process that a part of the mechanical energy is irreversibly transformed into thermal energy and then dissipated, during deformation of elastic elements. Two types of damping are available: material and structural damping.

[473] Moody, Hutcheon, and Grant, *Nuclear Forensics Analysis*.p.98. For further information about material consideration for other components with regard to UF6, see Nuclear Regulatory Committee (NRC), *10 CFR Appendix C to Part 110 - Illustrative List of Gaseous Diffusion Enrichment Plant Assemblies and Components under NRC Export Licensing Authority* (Dec. 2005 [cited Dec. 3 2008]); available from http://cfr.vlex.com/vid/illustrative-enrichment-assemblies-19616256.

[474] Dangers of Hydrofluoric Acid, Chemical Safety Office/EH & S UCLA Department of Chemistry and Biochemistry, *Safety Notes, Newsletter #4* (Feb. 1997 [cited Nov. 25 2008]); available from http://www.chem.ucla.edu/Safety/newsletter4.html.

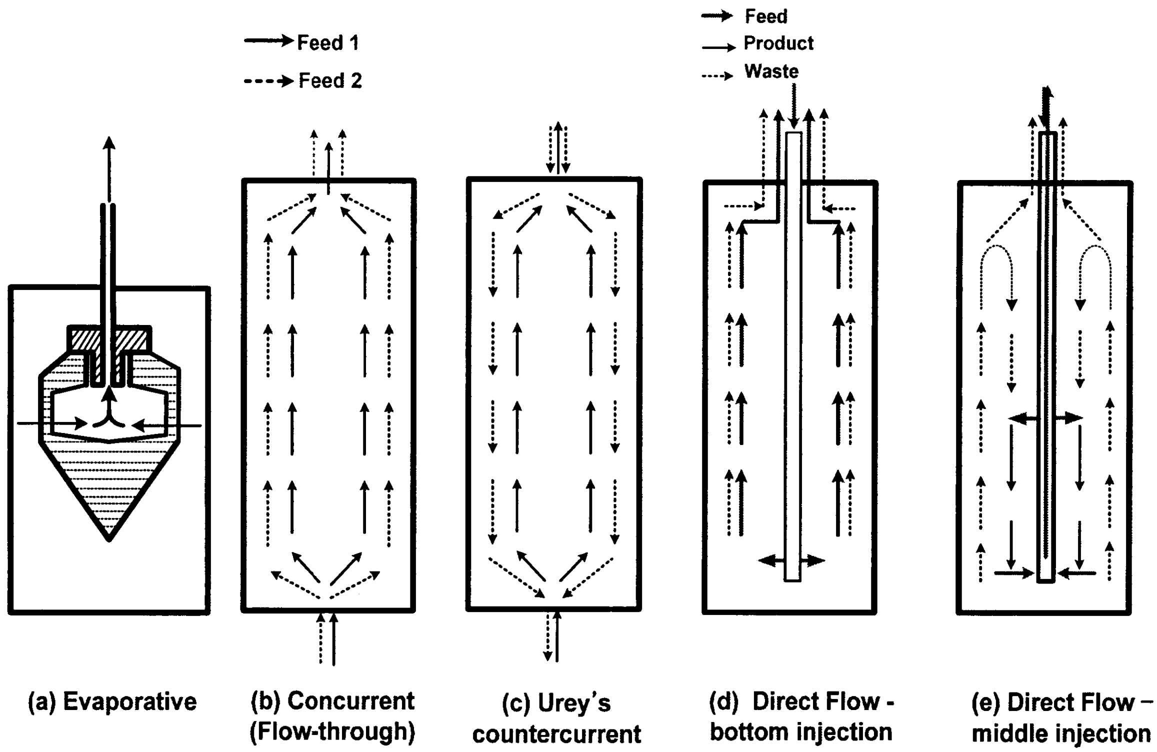

Figure 9.1 Different Types of Centrifuges [475]

The evaporative centrifuge [Figure 9.1 (a)] was first developed by R.S. Mulliken and experimental works were successfully conducted by J. W. Beams.[476] The use of vacuum-chamber centrifuges makes the centrifuge vibration-free and thermally isolated for the elimination of convection currents. In the concurrent centrifuge [Figure 9.1 (b)], a single stream of gas enters one end of a rotor through a hollow shaft, and two streams are taken off the other end, one from the periphery and the other near the axis. The design of the countercurrent centrifuge [Figure 9.1 (c)] was first developed by H.C. Urey and further developed by Konrad Beyerle, Wilhelm Groth (the ZC3 centrifuge), and Gernot Zippe (Zippe centrifuge).[477] In the countercurrent centrifuge, the two streams of gas are fed from opposite ends of the working chamber and run in opposite directions, making the multiplication of the elementary separation factor possible by amplifying the radial effect of separation. Figures 9.1 (d) and (e) show different designs of countercurrent gas centrifuges. In Figure 9.1 (d), the feed is injected at the bottom of the rotor, whereas the feed is injected in the middle of the rotor in Figure 9.1 (e).

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[475] Figures (a), (b), and (c) from Villani, *Isotope Separation.*, p.208 and figures (d) and (e) from Aleksandrov, "Comparison of Two Approaches to Using the Averaging Method for Analyzing Separation in a Gas Centrifuge.", pp.246-252.

[476] J. W. Beams, "High Speed Centrifuging," *Reviews of Modern Physics* 10 (1938).; J. W. Beams and C. Skarstrom, "The Concentration of Isotopes by the Evaporative Centrifuge Method," *Physical Review* 56 (1939).

[477] For more information about the countercurrent centrifuge development and principles, see Villani, *Isotope Separation.*, pp. 214-232.

The key question in the ***countercurrent system*** is how countercurrent flow can be effectively generated. Olander (1981) explains that thermal and mechanical drives result in a countercurrent flow: ***Thermal drive*** is accomplished by controlling the rotor wall or end cap temperatures, which affect radial pressure distribution, radial convection, and axial diffusion. In contrast, ***mechanical drive*** is generated by causing the rotating gas to interact with stationary objects inside the rotor in association with centrifugal forces and gravitational forces. [478]

Similarly, Borisevich et al. (1990) [479] suggest that a closed countercurrent flow in the centrifuge is generated by the axial flow into the working volume (***external component***) and the temperature distribution developing on the side wall of the rotor during the operation (***thermal component***). These two factors contribute to the flow pattern of the current in the centrifuge cylinder. Furthermore, centrifuges with bellows, baffle plates, and other parts will have the re-circulating flow, which makes for even more complexity to model.[480] Figure 9.1 (d) and (e) show how the internal flow regime can vary according to the point of feed injection into the rotor.

9.3.4 Other Considerations

In addition to aforementioned issues, a gas centrifuge machine involves very complex design factors such as power electronics and instrumentation and control issues. As for power electronics, a stable electricity supply using a high quality frequency converter is critical. The use of a fairly powerful motor can help overcome critical speeds in the rotor and bearings by rapid acceleration.[481] In the case of a supercritical rotor, the rotor must not stay long at the critical speed and make a fast jump around the range of the critical speed. These difficulties are partially addressed by very accurate balancing of the rotor and by achieving a swift transition through the resonance zone.

A frequency converter, one of key components of a GCEP is responsible for the power supply for the gas centrifuge machines and its design impacts the power of a motor. The power supply must accept AC input at the 50-60 Hz line frequency available from the electric power grid and provide an AC output at a much higher frequency (typically 600 Hz or more). The high frequency output from the frequency converter is fed into the high-speed gas centrifuge motors because the speed of an AC motor is proportional to the frequency of the supplied current. To this end, the centrifuge electric power supplies must operate at high efficiency, provide low harmonic distortion, and provide precise control of the output frequency.[482]

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[478] Olander, "The Theory of Uranium Enrichment by the Gas Centrifuge." pp.1-33. The term 'drive' connotes a means of generating the internal circulation in the rotor.
[479] V.D. Borisevich, E.V. Levin, and V.V. Naumochkin, "The Optimal Flow Structure in a Gas Centrifuge for Separating Uranium Isotopes," *Atomnaya Énergiya* 70, no. 1 (Jan. 1991)., pp.28-32.
[480] Kai, "Basic Characteristics of Centrifuges (IV).", pp.267-281.
[481] Villani, *Isotope Separation.*, p.213.
[482] GlobalSecurity.org, *Gas Centrifuge Uranium Enrichment.*

As for fission criticality constraints, fission criticality is not an issue with gas centrifuge machines. The gas-phase inventory is very small, and if the machine were to permit air leakage (with the resultant deposition of UO2F2 on the rotor walls), the machine would crash before a critical mass could accumulate.

9.4 Designing Cascade at GCEP

In order to obtain the desired enrichment of the U-235 isotope, it is necessary to connect a large number of centrifuges together in series and in parallel. These are called a cascade. Most technical-economic analyses of GCEPs show that the bulk of the cost is proportional to the number of centrifuges required. [483] This implies that an operator should minimize the number of centrifuges by using an optimized configuration and by minimizing replacement requirements through careful operation. There are two approaches for minimizing the number of centrifuges. First, designing an effective centrifuge machine can contribute to the increase of separation power and reduce the required number of gas centrifuge machines. Second, optimizing the configuration of cascades can also decrease the number of gas centrifuge machines required.

9.4.1 Stage and Cascade for Uranium Enrichment

A. Stages

A stage is the unit formed when individual gas centrifuge machines are connected in parallel as shown in Figure 9.2. This implies that all gas centrifuge machines in a stage would receive identical inputs and produce identical outputs, which are fed into the next stages.

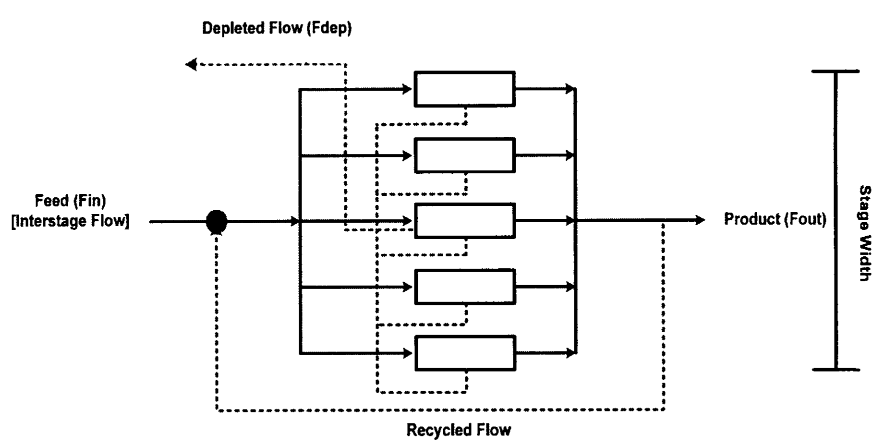

Figure 9.2 Schematic of a Stage

[483] Aleksandrov, "Separation Power of a Gas Centrifuge and Certain Errors in Optimizing the Centrifuge."

Stage cut and ***stage width*** are essential parameters to the description of a stage. Stage cut is the ratio of feed out of a stage to feed into a stage. Stage width is the number of gas centrifuges in the cascade. A stage cut is generally denoted by θ, and the work of stage can be described as follows:

$$F_{out} = F_{in} \times \theta \qquad (9.7)$$

$$F_{dep} = F \times (1 - \theta) \qquad (9.8)$$

where F_{in} is a flow fed into a stage (called "interstage flow"), F_{out} is a flow going to the next enriching stage, and F_{dep} is flow going back for recycle or tails stream.[484] In the ideal cascade, stage cut is approximated as

$$\theta \cong \frac{1}{2} - \frac{1}{4}\varepsilon \qquad (9.9)$$

where ε is the separative gain.[485] For an LEU cascade of centrifuges with a stage separation factor of 1.8, the stage cuts are typically about 0.43.

There are two kinds of stages based on what they do in a cascade, stripping stages and enriching stages. Enriching stages are the ones that enrich uranium. The number of enriching stages increases with the enrichment ratio of the desired product. In contrast, stripping stages work to decrease the tails assay, thereby saving uranium feed to produce a desired product enrichment ratio as shown in Figure 9.3. Trade-offs of having large number of stripping stages can be depicted in the Figure. In order to lower the concentration of depleted uranium, the number of stripping stages must be increased. Consequently, uranium feed consumption will be decreased. The greater the number of enriching stages, the higher the product of the cascade.

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[484] Stelio Villani, (1976). Figure 4.5 Generic stage in a cascade, p.102. Fin, Fout, and Fdep can be denoted by F, P, and W, respectively.

[485] Kawai et al., "Sensitivity Analysis of Ideal Centrifuge Cascade for Producing Slightly Enriched Uranium." For the analytical discussion of a stage cut effect, see Ichiro Yamamoto and Akira Kanagawa, "Effect of Stage Cut Deviation on Uranium Enriching Cascades Performances," *Journal of Nuclear Science and Technology* 13, no. 4 (April 1976)., pp.179-189.

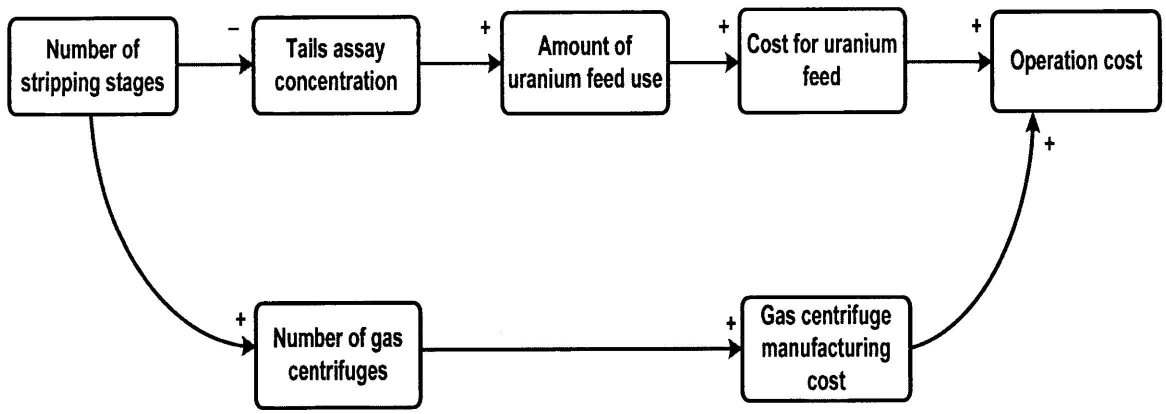

Figure 9.3 Role of the Number of Stripping Stages

B. Cascade

A cascade is composed of an array of stages. A cascade is actually a set of gas centrifuges designed to produce a desired uranium enrichment level. Centrifuges should be connected both in parallel and in series in a way to optimize given resources and efficiency. The formation of a cascade varies according to an operator's purposes and a given condition such as product flow rates, desirable enrichment ratio, feed and tails assay, and SWU capacity,

A cascade scheme can be classified in terms of either the presence of recycle or practicality. A cascade scheme can be divided into ***no-recycling cascade*** [(a) in Figure] and ***recycle cascade*** (countercurrent cascade) [(b) in Figure 9.4]. Countercurrent cascades can be further subdivided into symmetrical and asymmetrical cascades. If recycling or product streams jump a different number of stages, those schemes are called asymmetrical cascades [(c) and (d) in Figure 9.4]. For example, (d) in Figure 9.4, the product from stage 1 goes to stage 3 (i.e., jumping two stages), whereas the waste stream from stage 3 is recycled to stage 2 (i.e., proceeding to the very next stage).[486]

[486] Villani, *Isotope Separation.*

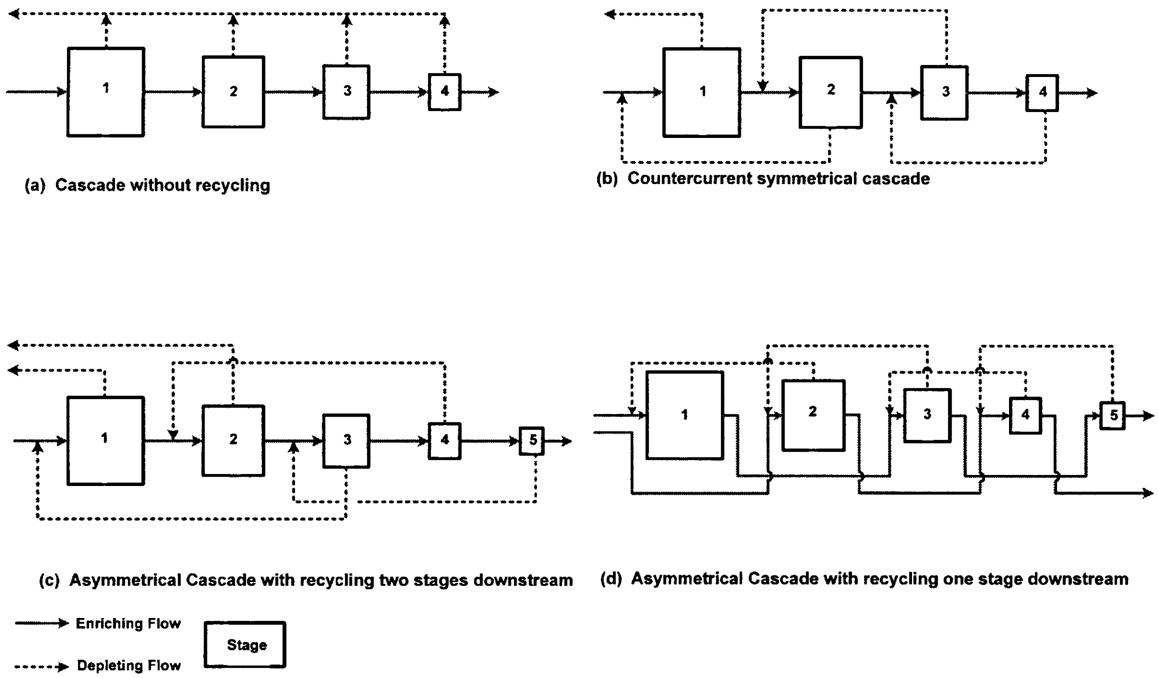

Figure 9.4 Various Cascade Schemes[487]

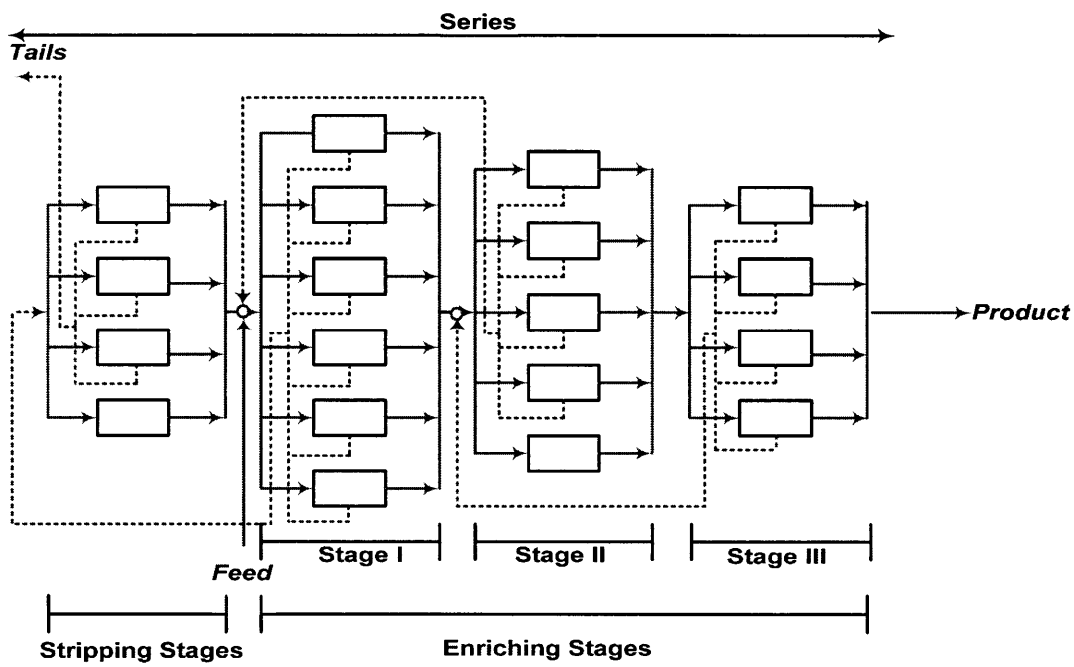

Figure 9.5 Detailed Drawing of a Cascade[488]

[487] Stelio Villani (1976), pp.100-101.
[488] Glaser, *Making Highly Enriched Uranium*.

The second way of a classifying cascade is dependent on whether it is ideal or practical. These designs refer to the shape of cascades. Figure 9.6 shows possible formations of cascades in terms of practicability.

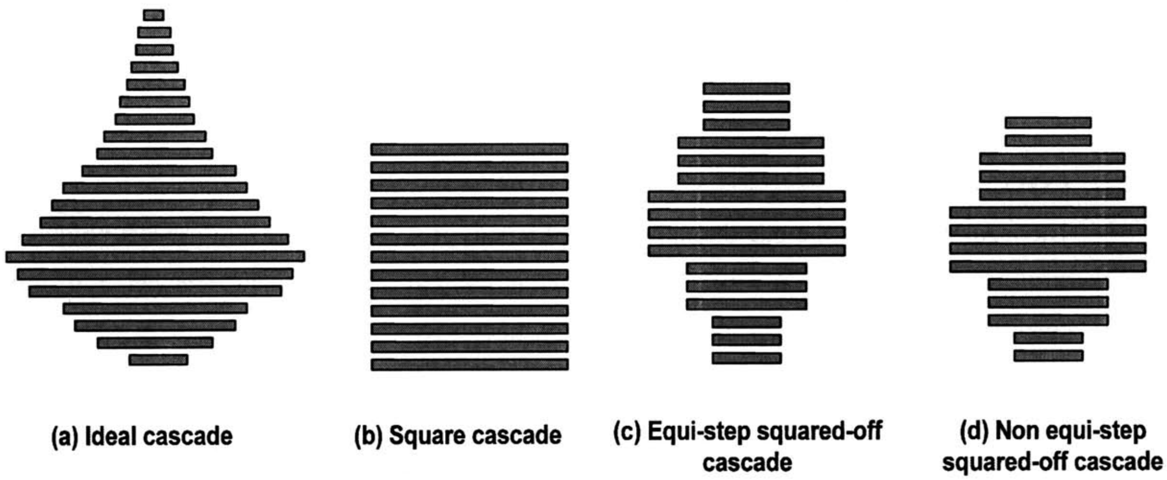

Figure 9.6 Ideal, Square, and Squared-off Cascade Schemes[489]

Figure (a) shows a typical shape of an ideal cascade. A cascade for gas centrifuge machines can approximate ideality very closely. The details about the ideal cascade are discussed in the next section. Figure 9.6 (b) shows a square cascade which is an extreme model that can offer the advantage of standardized manufacture of stages. All of the stages in the square cascade have the same values of stage feed rate and the stage separation factor. The square cascade can be optimized to the minimum number of stages per unit of product flow rate with fewer stages. However, the square cascade design would require more feed flow rate than the ideal cascade design for a given condition of product and tails assays. [490] Figure 9.6 (c) shows a squared-off cascade which has a number of adjacent stages with the same number of centrifuges. This approach reduces SWU losses and achieves the simplicity of performance calculation of square cascades, but the top and bottom stages would not optimal.[491]

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[489] The term, equi-step was used in the paper, Takashi Yamada and Bunpei Ishii, "Influence of Stage Separation Factor on Squared-Off Cascades," *Journal of Nuclear Science and Technology* 11, no. 2 (Feb. 1974)., pp.58-64. However, the shape of a cascade does not need to be symmetric. Geldenhuys (1979) has developed the method to design asymmetric cascades for different isotope enrichment based on mass conservation equations with linear algebra. G. Geldenhuys, "Design of an Asymmetric Ideal Cascade for Isotope Enrichment," *SIAM Rev.* 21, no. 3 (Jul 1979). pp. 390-394.

[490] B. Brigoli, "Cascade Theory," in *Topics in Applied Physics*, ed. S. Villani (New York, NY: Spring-Verlag, 1979)., pp.28-31.

[491] For more discussion, see Chuntong Ying, E. Von Halle, and Houston G. Wood III, "The Optimization of Squared-Off Cascades for Isotope Separation," *Nuclear Technology* 105 (Feb. 1994)., pp.184-189.

9.4.2 Design of Cascade

Since a gas centrifuge cascade can be constructed which is very nearly ideal, which is different than other uranium enrichment technologies, the design of ideal cascades is further discussed in this section.

A. Definition of Ideal Cascades

An ideal cascade is the most efficient arrangement of centrifuges. The ideal cascade can be defined in three ways:

- **SWU consumption**

  The ideal cascade is the one that minimizes the ratio of separative work to product produced by ensuring that streams of differing concentrations are never mixed together (no mixing condition).[492] This results in low energy consumption (No SWU is wasted by mixing flows of different concentrations).

- **Reflux ratio**

  The ideal cascade minimizes the ratio of ***total cascade flow to product flow***, thereby producing the largest possible amount of product for a given enrichment, tails assay and separative capacity (minimum reflux ratio).[493]

- **Equilibrium time**

  The cascade provides the shortest possible equilibrium time for a given product enrichment. This results in the smallest inventory. [494]

However, an ideal cascade is never achieved in practice for several reasons. The most challenging issue in an ideal cascade is to ensure the absence of mixing of streams of differing concentrations. This is not achievable even in a single stage because no individual centrifuge machine is identical in terms of separation. Stages receive a mixed input of the waste flow that is recycled back as well as the product flow of the previous stage. To achieve a ***no-mixing condition***, the two flows should be identical. The stage cuts need to be adjusted so the isotopic concentration of the waste flow is identical to that of the product flow from the preceding stage. Thus, the ideal cascade requires every stage to carry a slightly different flow from the ones adjacent to it. However, these adjustments in flow rates are too small to achieve, and it is too complex and expensive to manufacture all different machines for all different stages.[495]

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[492] Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation.*, p.104.
[493] Ibid., p.110 and p.115.
[494] Ibid. , p.110.
[495] Ibid, Barzashka and Oelrich, *Separation Theory*. One of possible methods to get around this problem is to make centrifuges in different sizes for every stage because theoretically optimal flow for every stage may correspond to a non-integer number of machines

B. Design of Ideal Cascade

A scale model shown in Figure 9.7 can be used to determine some properties of the cascade design. The horizontal dimension represents the number of stages, and the vertical dimension shows the flow rate of material at each stage. The ***total area*** corresponds to the total material flow rate in the cascade, which is proportional to the total separative power of the cascade (tonSWU/yr). The connection of the centrifuges in series would increase the enrichment level, while the total number of centrifuges in a stage determines the product flow rate.[496] In practice, if a fixed number of gas centrifuge machines are available, a designer must choose between a higher enrichment with a lower product rate and a lower enrichment with more product rate.

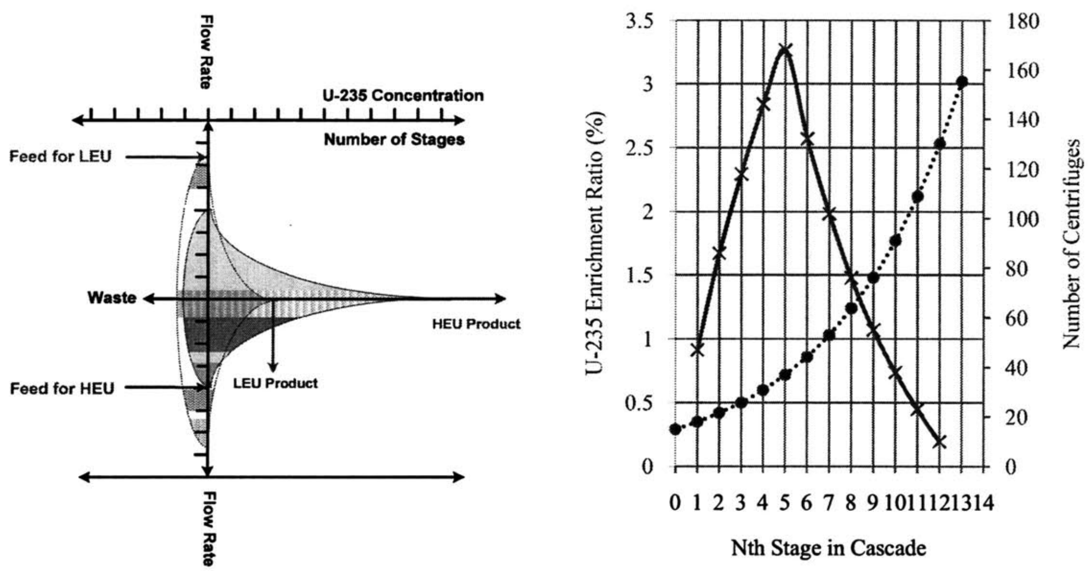

Figure 9.7 Scale Model of Ideal Cascades

Based on ideal cascade design, uranium enrichment ratios in stripping stages and depleting stages vary in exponential fashion as shown in Figure 9.7.[497] Figure 9.8 shows several possible designs of the ideal cascade. The numbers in gray bars denote the number of centrifuge machines connected at each stage.

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[496] Takanobu Ishida and Yasuhiko Fujii, "Chapter 2 Enrichment of Isotopes," in *Isotope Effects in Chemistry and Biology* ed. Amnon Kohen and Hans-Heinrich Limbach (Boca Roton, FL: CRC Press, 2005)., p.61. In Chemical Engineering, the design of cascade is limited by a reflux ratio ranging from minimum reflux ratio with infinite number of stages and total reflux ratio in which the product is not withdrawn from a cascade. These two ratios are obtained through the McCabe-Thiele diagram.

[497] Whitley, "The Uranium Ultracentrifuge: The Story of the Development of the Gas Centrifuge for the Separation of the Isotopes of Uranium."

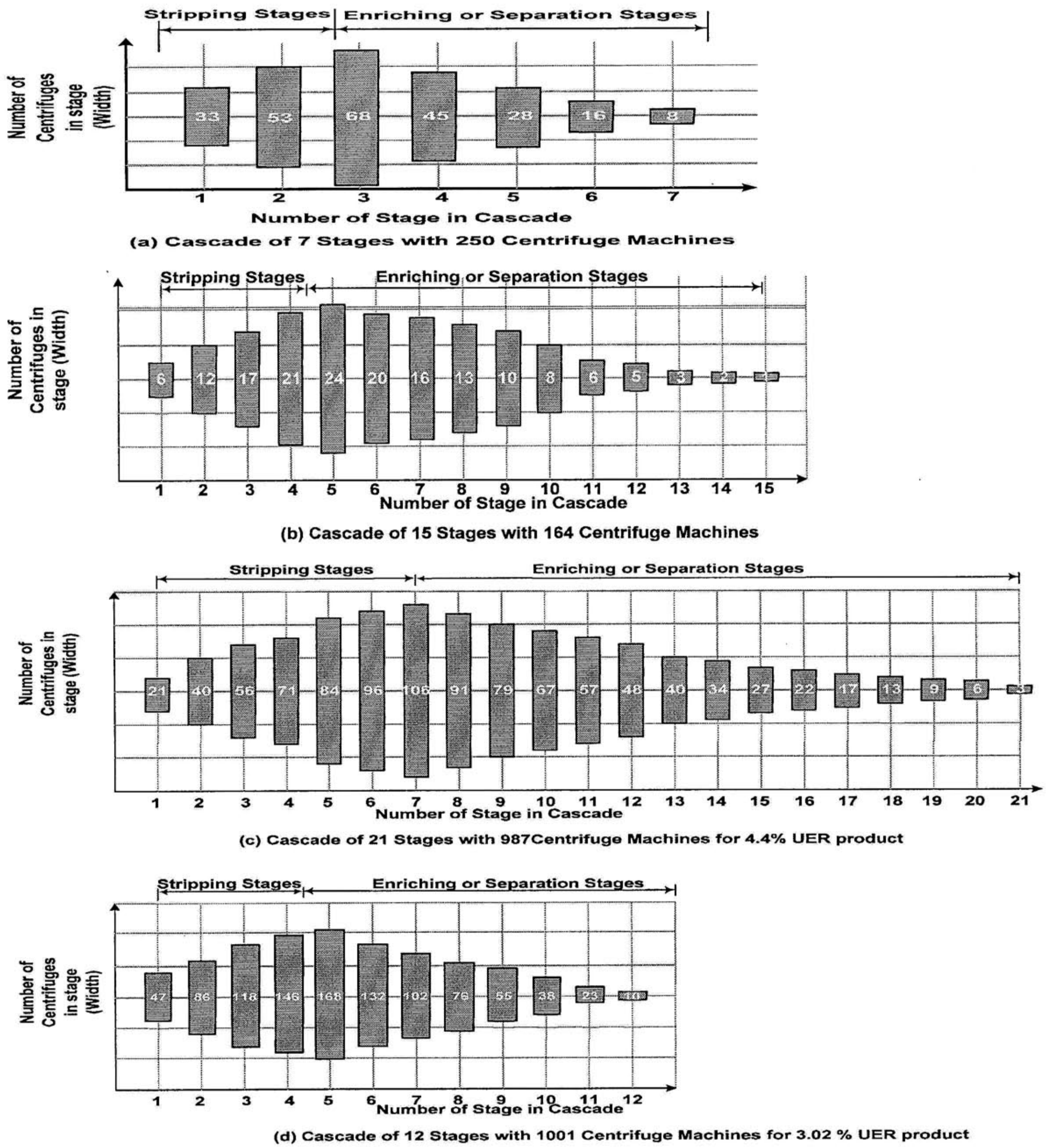

Figure 9.8 Example Designs of Cascade Configuration[498]

9.5 Optimization of a Cascade

For the effective operation of GCEP, a cascade formation should be optimized dependent upon the operator's objectives and constraints. A cascade of gas centrifuges is generally optimized to produce

[498] (a) from John Pirro, "The Layout of Centrifuge Cascades for Uranium Enrichment" (paper presented at the American Nuclear Society Winter Meeting, San Francisco, California, Nov.27-Dec.2 1977).. (b) from Houston G Wood, A. Glaser, and R. Kemp, "The Gas Centrifuges and Nuclear Weapon Proliferation," *Physics Today* (September 2008)., pp.40-45; (c) from Glaser, *Making Highly Enriched Uranium*.pp.88-95 ; and (d) from Whitley, "The Uranium Ultracentrifuge: The Story of the Development of the Gas Centrifuge for the Separation of the Isotopes of Uranium."

maximum separative power for a given product and tails assays. All parameters that are to be optimized are studied during the design stage and operators should follow the designed optimal operation conditions. However, a cascade design that ensures optimal efficiency is a very complex process. For example, the best operating conditions are settled in a way that minimizes total interstage flow. However, once that is done, it is no longer possible to avoid mixing process streams of different isotopic composition, and this would result in losses of SWU.[499] Thus, an optimal design will be different depending on the objectives that designers want to achieve. There has been a lot of research done to fined approaches to the optimization of cascades based on the designed goals and constraints. Table 9.4 shows a typical approach to the modeling of an optimal cascade.

Table 9.4 Procedure for Optimization

Step		**Factors for consideration**
1	**Set the objective**	•Desired isotopic composition of product, tails and feed •Desired withdrawal rate of cascade product
2	**Identify constraints**	•Technical capabilities: Separative power of a gas centrifuge •Economic constraints: gas centrifuge manufacture cost,[500] uranium feed cost, and energy cost, SWU cost
3	**Identify variables**	•Cascade values: product flow, feed flow, tails flow, total flow rate, inventory •Stage values: stage cut, stage separation factors, the flow rate per stage •Time values: equilibrium time, hold-up time
4	**Optimize key controlling variables**	•The number of stages and subsequent total flow rate

Kawai et al. (1973) categorized the parameters involved in optimizing cascade design as controlling variables and controlled variables.[501] For example, they identified the stage cut, the centrifuge and stage separation factor, and feed flow rate as controlling variables. In contrast, total flow rate, enrichment rates of product and waste at each stage, and separative work were designated as controlled variables. Palkin (1997) classified the parameters into six external parameters and internal parameters. The external parameters of a cascade are those that can be obtained by considering the cascade as a black box. The internal parameters are obtained by considering the internal mechanism, such as the interstage flow rates and compositions.[502] He formulated the optimization problem in terms

[499] Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation.*
[500] The minimization of the number of centrifuges for specific purposes is a very important optimization criterion in designing a cascade of centrifuges.
[501] Kawai et al., "Sensitivity Analysis of Ideal Centrifuge Cascade for Producing Slightly Enriched Uranium."
[502] Barzashka and Oelrich, *Separation Theory.*

of minimizing the total fluxes of the stages by determining internal parameters for the selected values of external parameters. [503]

9.6. General Layout of GCEPs

A cascade hall typically contains several cascades to produce the desired level of enriched uranium or even products with different enrichment ratio. An overall schematic of a cascade hall is shown in Figure 9.9. Shown are autoclaves, holdup drums, cascades, and desublimers. The flow process in a GCEP cascade hall is as follows: First, UF_6 passes through autoclaves, (a pressurized device for heating liquid UF_6 above its boiling point at normal atmospheric pressure). Gaseous impurities in the input feed are removed before it undergoes enrichment operation. Second, a holdup drum enables withdrawal of UF_6 gas during operation and the input feed is depressurized. Third, UF_6 is enriched through cascades. At the final stage, the product and the tails go through a desublimation process not only to compress UF_6 gas but also to remove impurities.[504]

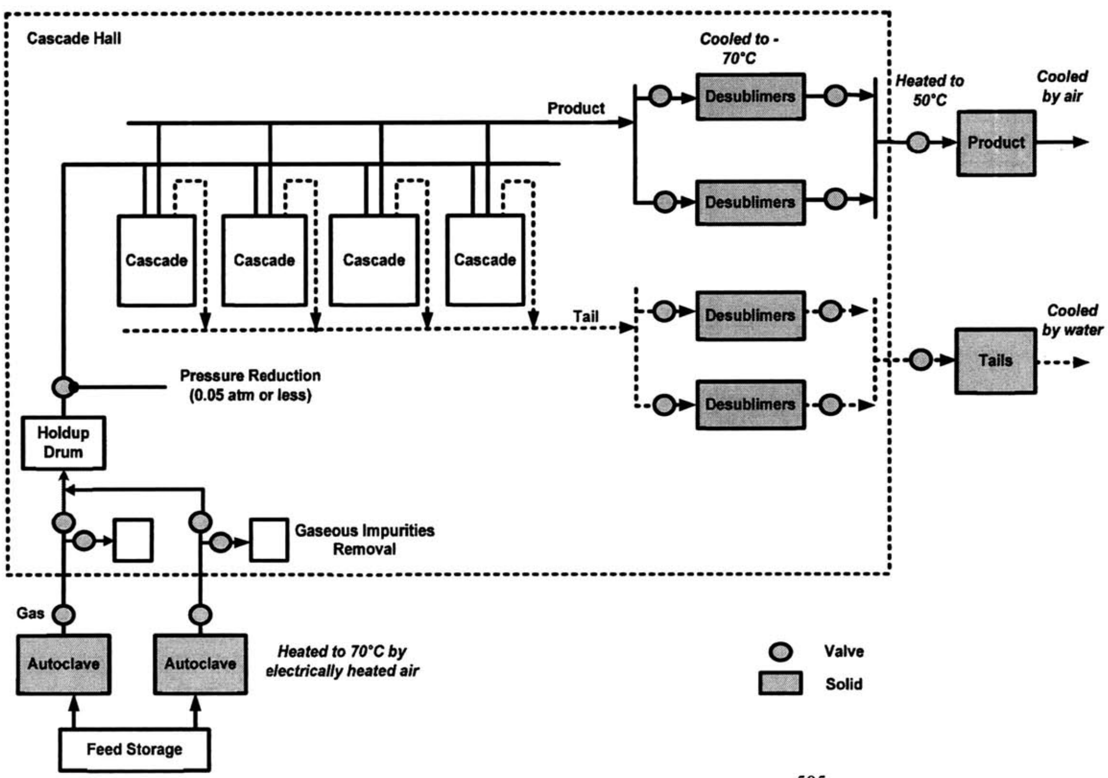

Figure 9.9 Block Diagram for Cascade Hall[505]

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[503] Palkin, V.A., Optimization of a cascade with arbitrarily specified separation coefficients of the stages, *Atomic Energy*, Vol. 82, No.4, pp.288-293, April (1997). See also Villani for further details.

[504] UF6 gas is the heaviest one in the world, so it typically goes through the final stage of enrichment operation.

[505] Figure from H.A. Elayat et al., "Systems Analysis of Safeguards Effectiveness in a Uranium Conversion Facility" (paper presented at the 45th Annual Meeting of the INMM, Orlando, FL, July 18-22 2004). For more explanation from the flow of UF6, see Bhupendra Jasani.

9.7 Operation of Gas Centrifuge Enrichment Plants

9.7.1 Operation Procedure

GCEPs are very sensitive, complicated, and they require a dedicated level of technological know-how in order to operate in an efficient fashion. The operation of gas centrifuges should be continuous because mechanical problems are particularly apt to occur. when they stop or resume operation. Even in case that there is no UF_6 inventory in a gas centrifuge, the machine itself should continue operation in a vacuum state. This also applies during batch recycling operation of uranium.[506] Operating procedures for GCEPs are shown in Table 9.5.

Table 9.5 Operation Procedures of GCEPs [Krass et al. (1983), p.108]

Step		Description
1	**Introduce material**	Filling material of the same initial isotopic composition at all stages
2	**Begin pump operation**	The pumps are started with the product extraction valves are closed.
3	**Operate under total reflux**	Operating under total reflux operation from the beginning of the enrichment operation until the concentration of U-235 reaches the desired level. The enrichment at the output of the top stage is monitored.
4	**Begin withdrawal of product**	Extracting the product by opening valves slightly after the concentration of U-235 in the top stage reaches the desired level
5	**Continue steady-state operation**	Operating at constant rate of enrichment

9.7.2 Causes of Gas Centrifuge Breakdown

Because a gas centrifuge machine is very sensitive to a shock, a continuous, stable operation should be ensured. In particular, the three issues should be carefully considered; vibration damaging, temperature and pressure, and impurities.

A. Mechanical Damage: Vibration

The most important issue with regard to the operation of GCEPs is related to the prevention of damage caused by vibration. This vibration can occur during startup and closing of enrichment operation when it is difficult to keep balancing a gas centrifuge machine, i.e., during acceleration and deceleration of gas centrifuges. Thus, typically an operator keeps running a gas centrifuge even if the gas centrifuge does not hold UF_6 gas. In addition, the aforementioned resonance frequency is another fact that causes breakdown of gas centrifuges.

[506] Personal communication with Dr.Forsberg (Jan. 20th, 2009)

B. Temperature and Pressure

Stationary centrifuge

The average temperature of the process gas during enrichment operation is typically 300 °K, slightly above room temperatures.[507] The vapor pressure of UF_6 at room temperature is about 0.15 atm.[508] Pressure in the gas centrifuge machine should be maintained below its sublimation vapor pressure at room temperature (20 °C or 68 °F) to prevent the solidification of UF_6. Moody et al., (2005) suggest that the gas load of a stationary centrifuge with a radius of 10 cm must remain less than ***$3.6x10^{-4}$ atm*** (or 0.00529 psi) in order to ensure the pressure at the rotor wall does not induce a phase change of UF_6 during operation.[509] Otherwise, the UF_6 will be desublimated to a solid state, which will cause the rotor to become unbalanced and crash.

Centrifuge during operation

Figure 9.10 shows the pressure gradient in the rotor during operation. Once the gas centrifuge machine begins operation, in the rotor, the wall has the highest pressure, whereas the center has the lowest pressure. The highest pressure must remain below 0.1 atm to prevent a phase change of UF6. The resultant pressure at the center of the rotor should make up a good vacuum, about ***$2.5x10^{-9}$ atm***.[510]

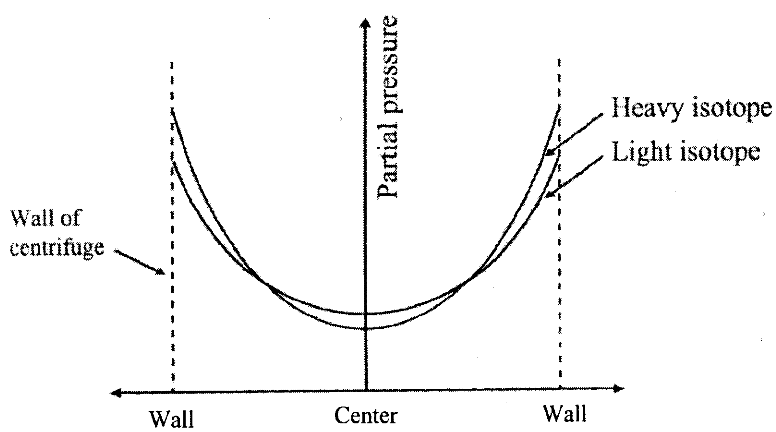

Figure 9.10 Distribution of Partial Pressures of Light and Heavy Molecules in an Operating Gas Centrifuge[511]

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[507] Jochen F. A. Delbeke, " Theoretical Analysis to Assess the Separative Power of Reconfigured Cascades of Predesigned Gas Centrifuges," *Industrial & Engineering Chemistry Research* 48, no. 10 (April 2009)., pp. 4960–4965.

[508] Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation*. This corresponds to 2.204 psi (1 atm is taken as 14.696 psi). Moody et al., suggest 0.1 atm.

[509] Moody, Hutcheon, and Grant, *Nuclear Forensics Analysis*.p.133. However, it should be noted that UF6 is fed into the machine while the rotor is spinning, otherwise, UF6 would leak out into the casing, where it would be pumped away by the vacuum system.

[510] Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation*. p.133.

[511] Moody, Hutcheon, and Grant, *Nuclear Forensics Analysis*., p.110.

C. Impurities in the UF_6 Gas[512]

Impure UF_6 complicates the uranium enrichment process and cannot be used as feed material for centrifuges.[513] Impurities can cause unbalancing of the centrifuge rotor and chemical reactions with metals in the centrifuge machine. Thus, impurities in UF_6 feed should be removed as much as possible before enrichment operation begins. These impurities can enter by several pathways, including in the initial feed and at different steps of the cascade. [514].

D. Criticality

Criticality problems arise in any process where enough fissionable material might collect to produce a self-sustaining nuclear reaction. This is not a serious problem when the process inventory is in gaseous form because the low density of the gas prevent reaching criticality. The use of low pressure UF_6 gas in a gas centrifuge plant will not allow criticality problems to arise in the cascade. But when UF_6 is treated in liquid or solid form, special precautions must be taken to make sure that no critical mass can ever accidentally be assembled.[515] There may also be criticality problems in the product-collecting area where the UF_6 gas is transformed into the solid phase or in the case of batch recycling operation.[516]

9.8 Off-Design Operation

There are always situations where an operator needs to change production rate or uranium enrichment level of the product or change the feed assay.[517] Any deviated operation from these optimum design values (off-design operation) will result in the decrease in efficiency and the overall cascade separative power.[518]

Figure 9.11 shows trade-offs with regard to adjusting the reflux ratio of a given cascade. A variation in reflux ratio affects the rate of production and the UER of the product. If an operator wants to increase the UER of the product, he may reduce reflux ratio which decrease the production rate as shown in Figure 9.11 (a). If a proliferator wants to minimize the use of uranium feed, he may allocate more SWU for stripping stages. The decision on whether an operator will operate off-optimal design

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[512] Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation.*, p.118.

[513] Sammy Salama and Elizabeth Salch, *CNS Research Story, Iran's Nuclear Impasse: Give Negotiations a Chance* (2006 [cited Feb. 15 2009]); available from http://cns.miis.edu/stories/060602.htm.

[514] V.A. Palkin and R.S. Komarov, "Method for Calculating and Optimizing a Cascade for Separating a Mixture of Isotopes with Impurities," *Journal of Atomic Energy* 98, no. 4 (Apr. 2005).

[515] Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation.*, p.11.

[516] Ibid., p.20.

[517] This can be the case of LEU use as input feed at LEU UEFs for HEU production. The use of LEU feed for HEU production will increase tails assay enrichment compared to the use of NU as a feed to UEFS.

[518] The loss resulted from off-design operation could be compensated by tuning some of the centrifuge parameters. However, wall heat constraints and corresponding issues with internal pressures will limit this compensative measure. Delbeke, " Theoretical Analysis to Assess the Separative Power of Reconfigured Cascades of Predesigned Gas Centrifuges.", pp. 4960–4965.

can be made based on various factors including the price of uranium, the price of SWU, the amount of uranium available, etc.

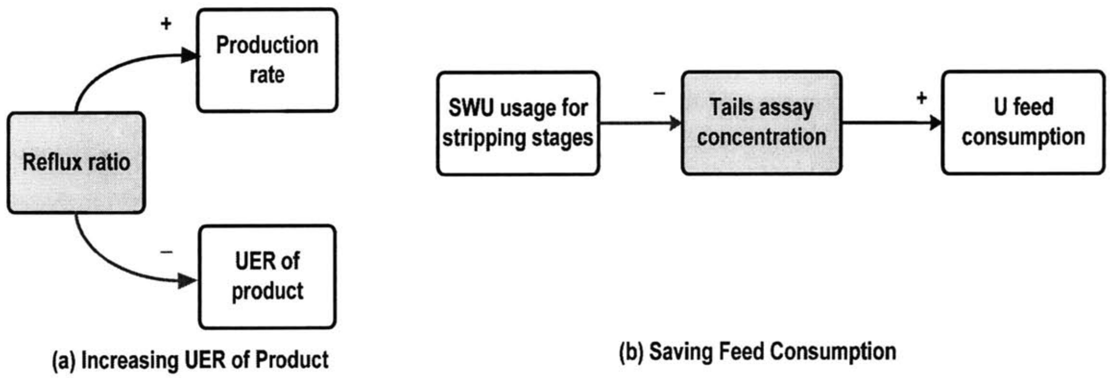

Figure 9.11 Trade-offs with regard to Off-Optimal Design Operation

9.9 Evolution of Gas Centrifuge Enrichment Technology

After the first successful operation of commercial GCEPs in the 1970s, GCEP technology has evolved in Russia, the United States, and Western Europe as shown in Figure. Like other technologies, GCEP technology spread out despite the technology holders' efforts to secure the technology mainly through human resources.

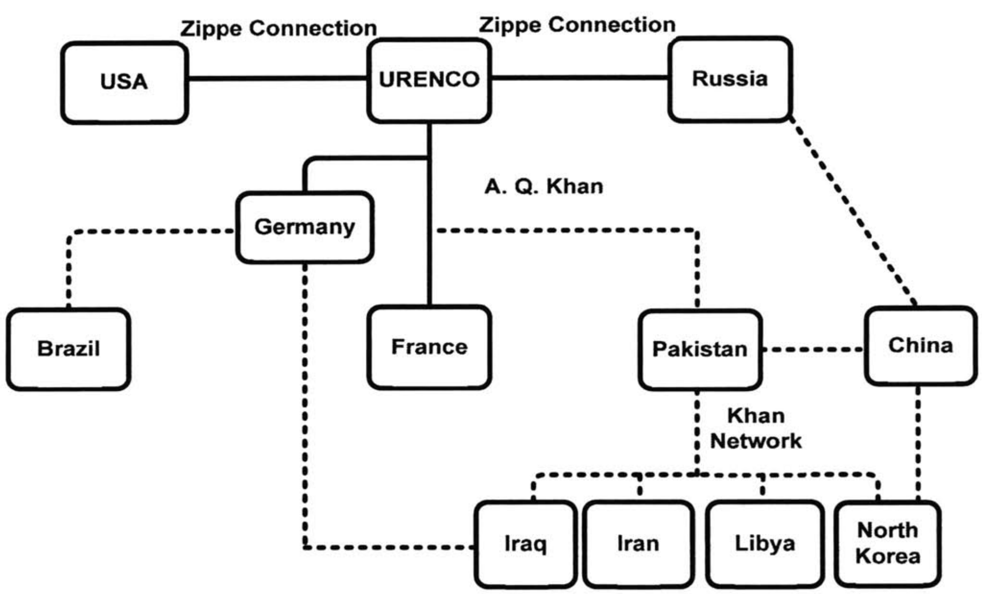

Figure 9.12 Genealogy of the Gas Centrifuge Enrichment Technology[519]

[519] Glaser, *Making Highly Enriched Uranium*.

Figure 9.12 shows how current GCEP technology holders obtained their gas centrifuge technology. While these holders claim that they had developed gas centrifuge technology through their own R & D programs without any external support, nearly all states acquired it through external assistance. In the case of Iraq, Karl Schaab, a German engineer who worked at MAN played a key role in its gas centrifuge development program until early 1990s.[520]

Table 9.6 Comparison between Pakistani Design and Other Designs of GCEP

	Pakistan				**American centrifuge**	**Urenco (TC-21)**	**Russia**
	P1	P2	P3	P4[521]			
Similar Design	SNOR /CNOR[d]	G2	URENCO 4M	SLM (TC-10)			
Deployment period	1960s-70s	1960s-70s	Early 1980s	Late 1980s	2000s	2000s	
RPM [c]	64,000		90,000				
Peripheral speed (m/s)	350	480 (500)	485	500	900 >700	770	700
Velocity	350	500	485	508			
Height	2m (1-2m)	1m	2m	3.2m	12m	5	<1
Diameter	100 mm	150 mm	n/a	150mm	60cm	20cm	n/a
Pressure	-	100 torr	-	-	-	-	-
Separation factor	-	1.28[f]	-	-	-	-	-
SWU/centrifuge	2-3 (1-3)	5-6 (5)	12 (11.6)	21	330 (300)	100 (40)	10
Rotor material	Aluminum	Maraging Steel	Carbon Fiber-Resin Composites (CFRC)				
kWh/SWU	100-300	50-60	-	-	-	-	-
SWU/area $[m^2]$	-	10~20	-	-	-	-	-

Notes
[a] Most values are from Alexander Glaser (2008) unless noted otherwise.
[b] Values in parentheses and Russian data are M. Miller's estimates[522]
[c] Nader Bagherzadeh, "IAEA's Report on Iran's on P2 Centrifuge Design, or is it really P3?," <http://www.uni-graz.at/yvonne.schmidt/P2_or_P3.pdf>
[d] SNOR (Scientific Nuclear Orbital Rotor or Scientific Nuclear Obreptitious Rotor) and CNOR (Cultivated Nuclear Orbital Rotor or Commercial Nuclear Obreptitious Rotor)
[e] SNOR is a subcritical single tube centrifuge, whereas CNOR is a supercritical six-segmented centrifuge.
[f] R.S. Kemp and A. Glaser (2007)

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[520] Institute for Science and International Security (ISIS), *Iraq's Acquisition of Gas Centrifuge Technology Part II: Recruitment of Karl Heinz Schaab*.

[521] For more information about P3 and P4 designs, see Mark Hibbs, "Pakistan Developed More Powerful Centrifuges," *NuclearFuel* 1 (2007).

[522] Miller, "Appendix I the Gas Centrifuge and Nuclear Proliferation." pp.35-41. His data includes P1, P2, Russia, Urenco and US design. However, it seems that he used the TC-12 data for Urenco design values.

Table 9.6 explains the generally accepted notion about the origin of GCEP technology in the world. As for proliferation purposes, P1, P2 and, presumably, P3 and P4 were proliferated by the Pakistanis. The P1 centrifuges use an aluminum rotor, and the P2-P4 centrifuges use a ***maraging steel*** or CRFC rotor. The largest centrifuge was developed in the US and is now called the American Centrifuge, which is about 12 meter high.

9.10 Rapid Improvement in Economics of GCEP

GDPs have been being replaced by GCEPs due to a rapid improvement in the economics of GCET for the following two reasons. First, the design of gas centrifuges have improved significantly as described in section 9.9. Second, the economic improvement of GCETs is a direct result of advances in other industrial fields. Thus, building GCEPs has become easier since many of the necessary technologies are borrowed from other industries. These specific cases include the following:

a. Composite fiber centrifuge (carbon fiber and related materials)

In the last decade, the aircraft industry has rapidly moved to building composite fiber aircraft. Currently, carbon fiber technology is quickly becoming the standard technology for new aircraft. This has resulted in a massive investment to improve fabrication technologies and drive down the cost of carbon composites. The aircraft industry is orders of magnitude large and centrifuge suppliers are benefiting from the supply industry being built to support commercial and military aircraft manufactures.

b. Solid state electronic motor controls

The cost of power electronics has dropped significantly given their large-scale use in variable frequency motor control systems. These controls improve the electrical efficiency of pumps in everything from refineries to water plants. What was once considered exclusive technology is now commercially available.

c. Design tools such as computational fluid dynamic codes for the chemical industry

The modeling of countercurrent flow in gas centrifuge machines can be more accurately designed using computational fluid dynamics software.

9.11 Features of GCEP for Proliferation

GCET has an advantage over other uranium enrichment technologies from many perspectives. As mentioned earlier, it is very hard for proliferators to set up GCET by themselves. However, once a GCEP is established through a variety of paths including nuclear black markets, a GCEP can be easily diverted for producing Highly Enriched Uranium (HEU). This is why GCET imposes an unusually significant challenge to the NPT regime. The features of a GCEP favorable to nuclear proliferation are as follows:

First, it has small inventory hold-up (a few grams per centrifuge) because of a low condensation pressures on the wall. Small inventory leads to short equilibrium time. A short equilibrium time means that the concentration of product would quickly reach the desired level of enrichment. In the case of P-2 type machines, the UF_6 inventory per centrifuge is about 2 grams. The total mass of uranium present in the cascade can be easily calculated by multiplying the number of gas centrifuge machines. A typical mass would be typically between several hundred grams and one kilogram. Therefore, typical throughput is on the order of milligrams per second, so an individual machine can be flushed in less than an hour.[523] However, the equilibrium time for GCEPs can vary over the shape of the cascade and the total UF_6 holdup in the cascade.[524]

Second, the high modularity of gas centrifuges yields the high flexibility in diverting GCEPs under any possible scenarios. A GCEP can be reconfigured for Weapons-Grade Uranium (WGU) production in a relatively short time-duration.[525] Third, a low level of effluents emission due to low operation pressures of the process gas and low energy consumption make gas centrifuge operation even much harder to detect. Fourth, most importantly, the high efficiency that is the result of its high separation factor leads to the advantage of producing HEU with GCEPs of very small size.

If a reference GCEP is set to a plant with a capacity to make HEU efficient for one bomb per year, it would have the capacity of 5,000~ 6,000 kgSWU/yr, the footprint of 160 square meter,[526] and the energy consumption of less than 100 kW.[527] Possible cases are shown in Table 9.7.

Table 9.7 Reference for Clandestine GCEPs

Case		Capacity	Footprint
A	Hypothetical minimum GCEP (by Dr. Glaser)	5,000-6,000 kgSWU/yr	160 square meter [528]
B	Pilot GCEP at Natanz	5,000 gas centrifuge (approximately 10,000 kgSWU/yr)	190m*170m[529]

Note: 1 SWU per 1 square meter would be a reasonable assumption.

[523] Wood and Morton, "Onsager's Pancake Approximation for the Fluid Dynamics of a Gas Centrifuge."
[524] Wood, Glaser, and Kemp, "The Gas Centrifuge and Nuclear Weapon Proliferation.", pp.40-45.
[525] Personal communication with Dr.Forsberg, It still requires additional time prior to starting-up of HEU production operation because the remaining uranium gas with different enrichment ratio must be washed out from the cascade.
[526] Glaser, *Making Highly Enriched Uranium.*
[527] Alexander Glaser, "Beyond A. Q. Khan: The Gas Centrifuge, Nuclear Proliferation, and the NPT Regime," *INESAP Information Bulletin*, no. 23 (April 2004).
[528] Glaser, *Making Highly Enriched Uranium.*
[529] David Albright and Corey Hinderstein, *The Iranian Gas Centrifuge Uranium Enrichment Plant at Natanz: Drawing from Commercial Satellite Images* (ISIS, Mar. 14 2003 [cited Jan. 30 2009]); available from http://www.isis-online.org/publications/iran/natanz03_02.html.

It could therefore be small and thus be indistinguishable from many other industrial buildings. The small size of gas centrifuges allows them to be operated in hardened underground facilities which even protect them from military strikes. And such a small GCEP (say producing enough HEU for a few nuclear weapons per year) would have great strategic significance for Non-Nuclear Weapons States (NNWS). Considering all of factors mentioned above, it would be a most challenging task to detect the existence and operation of small-sized clandestine facilities with currently available detection techniques. Figure 9.13 shows the characteristics of GCEPs and its impact to nuclear proliferation.

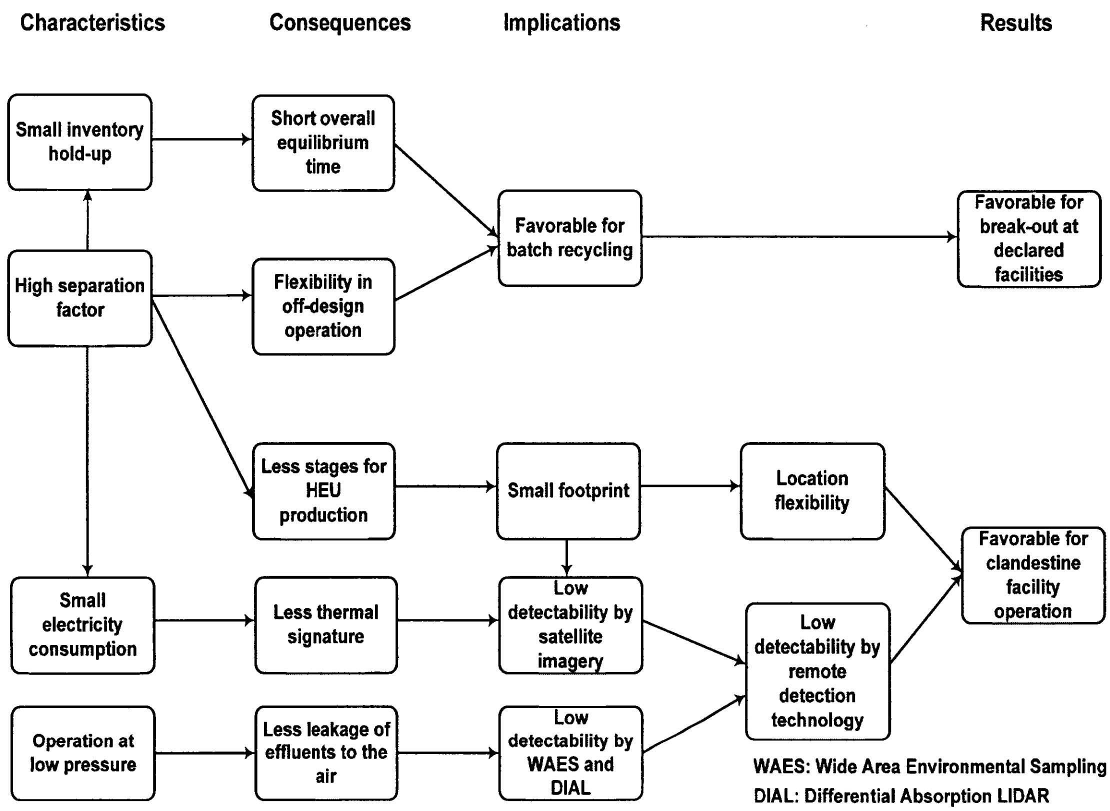

Figure 9.13 Features of Gas Centrifuge Technology and Influences to Proliferation

9.12 Conclusion

The design and features of GCET was reviewed. A gas centrifuge machine is a very complex and sensitive device that requires a high level of technology. The gas centrifuge technology still remains one of the finest multi-engineering projects in the world because it requires a high level of technology in mechanical, electrical, materials, electronic, metallurgic and chemical engineering. Even though the theoretical information is available to the proliferators, its use requires highly sophisticated equipment to actually construct and technological know-how to operate GCEPs.[530] However, the spread of GCET over the last several decades has allowed proliferators to jump those technological barriers. GCET will remain as the most promising enrichment technology for both the nuclear fuel cycle and nuclear weapons programs because of its high efficiency until the next generation technology, most likely Laser Enrichment Technology (LET), becomes commercially available.

[530] The process data, pressure, flow and other variables are very critical information in operating uranium enrichment facilities.

CHAPTER 10 IAEA SAFEGUARDS AT GCEPS

10.1 Introduction

The most important safeguards approach for the nuclear cycle is the one for a Gas Centrifuge Enrichment Plant (GCEP) because of its excellent proliferation-prone features. The development of a safeguards approach to GCEPs began in the late 1970s and research has continued for more than three decades. But a robust safeguards approach for GCEPs that can guarantee the non-existence of proliferation activities has not been achieved. The purpose of this chapter is to discuss and understand the current status of safeguards for GCEPs and to propose the direction in which the IAEA should continue to realize a mature safeguards approach to GCEPs.

The main weakness of the standard safeguards approach for GCEPs is the lack of standardized IAEA Safeguards for GCEPs. This is because of the short history of a safeguards approach to GCEPs, the proliferation sensitivity of Gas Centrifuge Enrichment Technology (GCET), and the different positions for the use of GCET by the gas centrifuge technology holders. In order to figure out these issues, a systematic framework for a safeguards approach to GCEPs should be established as a guiding tool. To this end, this chapter is composed of four parts: (i) the conceptualization of safeguards framework, (ii) the application of safeguards components to safeguards framework, (iii) the identification of problems, and (iv) possible solutions to the identified problems. This work is applicable not only to Uranium Enrichment Facilities (UEFs) but also to other types of nuclear fuel cycle facilities.

10.2 History of IAEA Safeguards at UEFs

The implementation of IAEA safeguards at Uranium Enrichment Facilities (UEFs) was far behind those for other types of nuclear facilities. The IAEA has safeguards experiences for Uranium Enrichment Technologies (UETs) of gaseous diffusion, gas centrifuge, and aerodynamic (or vortex tube) types. Only safeguards experiences for GCEPs and GDPs are reviewed here only because the aerodynamic facility (at Pelindaba Nuclear Research Center in South Africa) had been dismantled. The IAEA began safeguards inspections at URENCO plants in 1979 on an ad-hoc basis after URENCO began commercial operations at Almelo and Capenhurst in 1976.

10.2.1 Safeguards Experiences for Commercial GCEPs

URENCO of the United Kingdom, Germany and the Netherlands, and the MINATOM (Ministry for Atomic Energy) / Rosatom Nuclear Energy State Corporation (Rosatom) of Russia are among the major corporations that produce enriched uranium using GCET.[531] Among these major corporations, only URENCO's GCEPs have been under safeguards. On the contrary, AREVA and Minatom/Rosatom have never been inspected by the IAEA. The first IAEA inspection for GCEPs began in the late 1970s at URENCO's GCEPs initially on an ad-hoc basis. Inspections were then continued by a joint team from both the European Atomic Energy Community (EURATOM) and the IAEA. This was followed by a couple of safeguards projects as described below. However, most of safeguards experiences of the IAEA have been accumulated through inspection activities from URENCO facilities.[532]

A. U.S. Enrichment Safeguards Program

The U.S. conducted the U.S. Enrichment Safeguards Program in 1978 to design, develop, evaluate, and implement an effective international safeguards approach for GCEPs. In the United States, a small scale GCEP at Portsmouth Plant in Piketon, Ohio, began construction in 1977. The Portsmouth GCEP was under IAEA safeguards from August 1983 to July 1985. But it was shut down after a short period of operation in the mid 1980s.[533] Therefore, the program terminated in 1985. Since then, no commercial GCEPs have been operated in the U.S.[534] However, when GCEPs are completed in the U.S. (i.e., USEC plant in Ohio, LES/NEF plant in New Mexico, and the AREVA Eagle Rock Enrichment Facility in Idaho), they will be offered by the U.S. for IAEA safeguards.

B. Hexapartite Safeguards Project (HSP)

The actual beginning of safeguards development for GCEPs started in the early 1980s as the ***Hexapartite Safeguards Project (HSP)***, which lasted from November 1980 to March 1983. Neither INFCIRC/66- nor INFCIRC/153-type safeguards includes safeguards approaches for any type of facility. INFCIRC/153 type safeguards are limited to the recognition of an isotope separation plant in its paragraph 106.[535] The HSP was initiated by eight participants including the centrifuge technology holders of URENCO such as Germany, the Netherlands and Great Britain, as well as Japan, Australia, the United States, the IAEA and the Euratom.

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[531] AREVA is currently constructing a new gas centrifuge enrichment facility in France – Georges Besse II – with first deliveries expected for 2009. On December 30, 2008, AREVA Enrichment Services, LLC (a subsidiary of AREVA NC, Inc.), submitted an application to the U.S. Nuclear Regulatory Commission (NRC), seeking a license to construct and operate a gas centrifuge uranium enrichment facility in Bonneville County, Idaho, known as the Eagle Rock Enrichment Facility.

[532] Friend, "Urenco's Views on International Safeguards Inspection". Nuclear Weapon States (NWS) are not obligated to place their enrichment plants under IAEA safeguards.

[533] IAEA inspections were ad-hoc inspections, pending completion of a facility attachment for the plant.

[534] D. W. Swindle, "Realities of Verifying the Absence of Highly Enriched Uranium (HEU) in Gas Centrifuge Enrichment Plants," (Martin Marietta Energy Systems, Inc., 1990).; B. McGinnis et al., "Gas Centrifuge Enrichment Facilities in the United States - IAEA Safeguards Implementation" (paper presented at the Proceedings of the 46th Annual Conference of the Institute of Nuclear Materials Management (INMM) Phoenix, AZ, July 10-14 2005).

[535] Para.106 "Facility" means: (a) A reactor, a critical *facility*, a conversion plant, a fabrication plant, a reprocessing plant, an isotope separation plant or a separate storage installation. Conversion plants and fabrication plants were first mentioned in INFCIRC/66/Rev.2 (1968).

The HSP was launched to reach an agreement on an international safeguards approach for Low Enriched Uranium (LEU) Gas Centrifuge Enrichment Plants (GCEPs). The Goal of HSP was to maximize the effectiveness of safeguards while expanding a consensus from all parties of safeguarders and technology holders as follows:

- To minimize inspectorate resource requirements for verification from the standpoint of inspectors;
- To minimize the risk of sensitive information and technology leakage to the inspectorates;[536] and
- To minimize the additional operation cost resulted from intrusiveness by inspection.[537]

In March 1983, the HSP agreed on a safeguards approach to GCEPs, which is called ***Limited Frequency Unannounced Access*** (LFUA), subject to INFCIRC/153-type agreements. The LFUA was a very important first step in the development of safeguards for GCEPs. However, the application of HSP's proposal was confined to only HSP member states. The question of undeclared feeds, materials, and activities was not addressed because these were all beyond the scope of the original HSP. The IAEA put in place full-scope safeguards verification at all URENCO plants (including Gronau that started production in 1985) during the period 1984-1986 based on HSP principles and with agreed facility attachments.

C. Tripartite Enrichment Project

Russian GCET is distinct from those of URENCO and USEC. Thus, GCEPs based on Russian GCET require a different safeguards approach from the HSP. For example, Russian gas centrifuges provide a greater degree of operational flexibility in the piping arrangement than URENCO-type gas centrifuges. Also, the Russian ones are made out of steel which reduces the sensitivity of monitoring instruments.[538] In 1993, China offered its Russian-supplied Shaanxi GCEP for IAEA safeguards. From 1997 to 1999, the IAEA, the Ministry of the Russian Federation on Atomic Energy (MINATOM), and the China Atomic Energy Authority (CAEA) conducted the Tripartite Enrichment Project (TEP) at the Shaanxi GCEP in China. The TEP was designed to develop a safeguards approach for GCEPs built using the Russian GCET. In addition to the issue of different the technological features of the Russian GCET, the isolated location of Shaanxi GCEP made IAEA inspectors' travel conditions ineffective to achieve the

[536] Peixoto and Vinhas, "Information Protection When Applying Safeguards to Centrifuge Enrichment Facilities."
[537] Laughter, "Profile of World Uranium Enrichment Programs - 2007, ORNL/TM-2007/193."
[538] A. Panasyuk et al., "Tripartite Enrichment Project: Safeguards at Enrichment Plants Equipped with Russian Centrifuges," (2002). Steel has greater gamma-ray attenuation than aluminum because of its higher mass attenuation coefficient.

unpredictability of "LFUA." Nevertheless, the TEP concluded that the safeguards objectives of the IAEA could be achieved in a satisfactory and cost-effective fashion.[539]

10.2.2 Safeguards Experiences for Gaseous Diffusion Plants (GDPs)

It is worthwhile to look at safeguards approach for GDPs because some of those experiences at GDPs are applicable to GCEPs. Although they have different features, for both types of facilities use uranium hexafluoride gas (UF_6) as a feed for enriching uranium. In this regard, it is beneficial to review safeguards experiences about GDPs. The first GDP subject to international safeguards was the small scale GDP at Pilcaniyeu in Argentina and it has been under IAEA safeguards since 1993.[540] The U.S. has more extensive experience in the application of IAEA safeguards at GDPs from a verification experiment conducted at the Portsmouth Gaseous Diffusion Plant (PGDP) in the late 1990s. In April 1996, the US added the PGDP to the list of facilities, and it became eligible for the application of IAEA safeguards, following President Clinton's Presidential Decision Directive 13 of 1993, which offered excess fissile material no longer needed for national security for IAEA inspections. The first IAEA inspection at PGDP was conducted in December 1997 and followed by a verification experiment with a variety of safeguards measures. As a result, valuable experiences about safeguards approaches were obtained. This information is also applicable to GCEPs.[541]

10.3 Current Status of IAEA Safeguards at GCEPs

According to Laughter (2007), it is reported that there exist 13 countries that have GCEPs and 15 GCEP in place. Currently, only eight out of the thirteen states that have GCEPs are under IAEA safeguards and they are shown in Table 10.1.

Table 10.1 Status of Safeguards Application to GCEPs

	GCEPs	Under safeguards	Not under safeguards	Percentage
Countries	12 [a]	8[a] (6) [b] [Group A and B]	~5	66.7% (8/12)
Facilities	15 [c]	(9) [b]	~6	60% (9/15)

(Continued)

[539] Ibid. and International Panel on Fissile Materials (IPFM), "Global Fissile Material Report 2008: Scope and Verification of a Fissile Material (Cutoff) Treaty."
[540] A. D. Bonino et al., "DOE-ARN Proposed Method to Verify Uranium Inventory at the Picaniyeu Gaseous Diffusion Enrichment Plant" (paper presented at the 38th Annual Meeting of Institute of Nuclear Materials Management, Phoenix, AZ, July 21-24 1997).
[541] David Gordon et al., "BNL-65714."

Notes
[a] INFCIRC/640 (2005), para.128. The 12 countries are Argentina, Brazil, China, France, India, Iran, Japan, Pakistan, Russia, the U.S. and three URENCO states (Germany, Netherlands, and the UK)[542]
[b] Numbers in parentheses were obtained from McGinnis et al., (2005).[543] They claim that nine GCEPs in six countries are under safeguards, which are three URENCO States, Brazil, China, and Japan. However, INFCIRC/640 includes Argentina and Iran as countries under safeguards.
[c] Number of facilities under operation or stand-by.

For this study, we grouped states that have GCEPs into five categories from the viewpoint of safeguards application as shown in Table 10.2. Most safeguards experience for GCEPs has been obtained from URENCO states and Japan.[544] Hence, it is worth studying safeguards framework applied to URENCO states. Based on the result, safeguards application levels of Group C, D, and E and clandestine GCEP holders should be enhanced to that of URENCO states. The results of on-going safeguards research in the U.S. can be added to the standard features of future safeguards framework for GCEPs. Table 10.3 shows current status of safeguards application for GCEPs in Group C states.

Table 10.2 Classification of States with Confirmed GCEPs according to Safeguards Application

Group	Features	States[545]
A	High level of safeguards experience	URENCO States , Japan[546]
B	No GCEPs under safeguards now, but developing safeguards for future inspections	U.S.
C	Under limited safeguards, but not much experience	Brazil, China, Iran, Argentina
D	Not under safeguards as Nuclear Weapons States	France, Russia
E	Not under safeguards, Non-member to the NPT	Pakistan, India

Note: This classification is based on the author's subjective opinion.

[542]IAEA, "INFCIRC/640: Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report Submitted to the Director General of the International Atomic Energy Agency," (2005). Argentina has only a Gaseous Diffusion Plant (GDP) and it is under safeguards. However, Argentina is going to a build joint GCEP with Brazil.
[543] McGinnis et al., "Gas Centrifuge Enrichment Facilities in the United States - IAEA Safeguards Implementation".
[544] Japan has had GCEPs at Ningyo-Toge (now shut down) and Rokkasho-Mura (currently operating) under IAEA safeguards since the HSP in 1983.
[545] Para.128 in INFCIRC/640 (2005). For the details of enrichment programs in each country, see Laughter, "Profile of World Uranium Enrichment Programs - 2007, ORNL/TM-2007/193.".
[546] *Rokkasho-mura* uranium enrichment plant under IAEA safeguards (began operation in 1992). Office of Technology Assessment U. S. Congress, *Nuclear Safeguards and the International Atomic Energy Agency* (Washington D. C.: U. S. Government Printing Office, June 1995).; and *Ningyo Toge* Pilot Enrichment Plant in Japan had not yet reached the stage of decommissioning (started in 2000) to be removed from safeguards; thus, inspections were performed very infrequently. McGinnis et al., "Gas Centrifuge Enrichment Facilities in the United States - IAEA Safeguards Implementation".

Table 10.3 Safeguards Application in Group C States

State	Current status	Reference
Brazil	Resende Enrichment Plant under safeguards since November 2004	Wise Uranium Project[547]
China	Chinese Shaanxi GCEP under Voluntary Offer Safeguards Agreement since 1997.	Panasyuk et al., (2002)
Iran	Natanz pilot GCEP since December 2003	Iran Watch[548]

10.4 Safeguards Framework Development

10.4.1 Structure of Safeguards Framework

The IAEA and several nonproliferation research groups had been proposing safeguards for GCEPs until the IAEA formulated a new safeguards approach for GCEPs that correct many of deficiencies of the HSP approach. But those studies still lack a framework to synchronize efforts effectively for nuclear nonproliferation. The first step is to define safeguards objectives for achieving the nonproliferation of nuclear weapons. Each type of IAEA safeguards agreement has its own objective. For example, for INFCIRC/153 type safeguards, the objective of safeguards is stipulated in paragraph 28 as,

> *"**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."*

The description above can be defined as a general safeguards objective because it is generally applicable to all types of nuclear facilities. For a specific type of nuclear facility, safeguards objectives can be further defined by considering the features of the facilities in the form of the list of proliferation activities to be detected. This list is called specific safeguards objectives in this paper. In addition, the detection of proliferation activities for a different type of facilities can be complemented by adding certain conditions including a required time to meet timeliness and detection probabilities. We will refer to these conditions as detection goals.

Once specific safeguards objectives and safeguards goals are set up, the safeguarders should develop approaches for achieving the safeguards objectives, for example, regimes for inspection and systems for inspection. Safeguards approaches will set the rights and capacities of safeguarders in the

547 Wise Uranium Project, *Uranium Enrichment and Fuel Fabrication - Current Issues (Other Countries)*, (July 30, 2009) <http://www.wise-uranium.org/eproj.html>

548 Iran Watch, *Iranian Entity: Natanz* (2007 [cited June 18 2009]); available from http://www.iranwatch.org/suspect/records/natanz.html.

conduct of their inspection tasks. Features of different types of nuclear facilities are considered in the development of safeguards approaches.

The next step is to identify what inspectors have to do in order to achieve safeguards objectives within the capacities of a developed safeguards approach. However, safeguards approaches can be developed after the IAEA identifies inspectors' tasks in a way that can support inspection activities. Thus, safeguards tasks and safeguards approaches can be developed in parallel. The last step is to identify or develop measures that will help inspectors to perform their tasks such as inspection techniques and inspectors' activities.

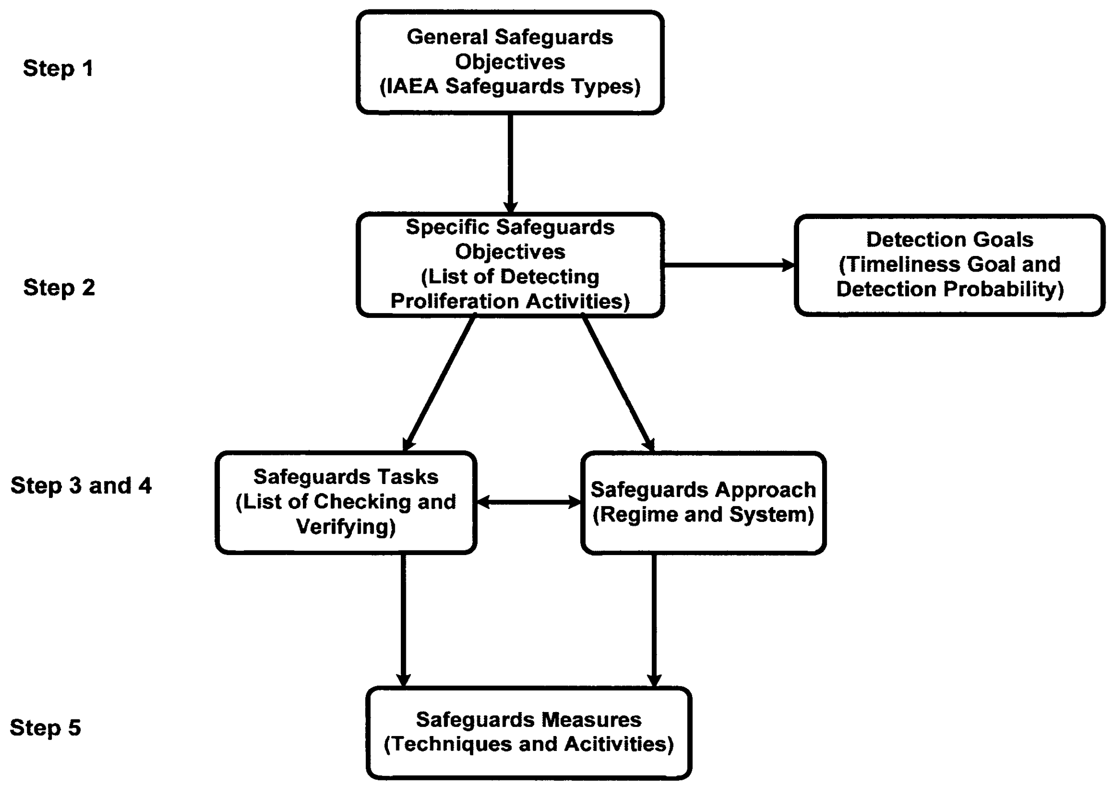

Figure 10.1 Concepts for Developing Safeguards Framework[549]

10.4.2 Specific Safeguards Objectives for a GCEP

This objective is the basis for detailed and specific inspection goals for inspecting each facility.[550] The IAEA declared three main specific safeguards objectives for a GCEP: [551]

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[549] The terms of verification and safeguards are interchangeably used in many safeguards documents such as verification objectives, verification tasks, verification approach, and verification measures.

[550] "INFCIRC/640, Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report Submitted to the Director General of the IAEA."

[551] Friend, "Urenco's Views on International Safeguards Inspection".; W. Bush et al., "IAEA Experience with Environmental Sampling at Gas Centrifuge Enrichment Plants in the European Union," (Austria: IAEA, 2004).

• **Specific Safeguards Objective #1**

To detect production and diversion of a significant quantity (SQ) of uranium with enrichment greater than declared, especially, Highly Enriched Uranium (HEU)

• **Specific Safeguards Objective #2**

To detect diversion of a significant quantity (SQ) of declared uranium materials, including Low Enriched Uranium (LEU), Depleted Uranium (DU), and Natural Uranium (NU)

• **Specific Safeguards Objective #3**

To detect LEU production in excess of declared amounts using undeclared uranium

The consensus made among HSP members was that HEU production posed a greater proliferation risk than LEU diversion because of shorter ***conversion time*** to make nuclear weapons. Considering conversion time and material form, the IAEA set timeliness goals for each specific type of nuclear material. Detection goals for safeguarding nuclear material at GCEPs are given in Table (10.4)

Table 10.4 Detection Goals of Specific Safeguards Objectives for GCEPs [552]

<table>
<tr><th>Specific Objective</th><th colspan="2">UER/ Mass</th><th>Timeliness Goals</th><th>Detection probability</th></tr>
<tr><td>#1</td><td>1 SQ HEU</td><td>Unirradiated direct-use material</td><td>Within one month</td><td>High confidence (HSP report)</td></tr>
<tr><td>#2</td><td>1 SQ LEU
10 MT NU
20 MT DU</td><td rowspan="2">Unirradiated indirect-use material</td><td>Within one year</td><td>50%</td></tr>
<tr><td>#3</td><td>1 SQ LEU</td><td>Within one year</td><td>50%</td></tr>
</table>

10.4.3 Safeguards Tasks

An array of technical verification tasks can be developed in order to achieve each safeguards objective. For GCEPs, identified safeguards tasks are as follows: [553]

• **For safeguards objective #1**

- verify the Uranium Enrichment Ratio (UER) of UF_6 collected at any place agrees with the declared UER

[552] Timeliness goals and detection probabilities are quoted from IAEA, *IAEA Safeguards Glossary 2001 Edition*. and B.D. Boyer, *Safeguards Approaches for Gas Centrifuge Enrichment Plants: LANL Safeguards Systems Course - Pilot 2008* (July 1 2008 [cited Jan. 1 2009]); available from http://web.mit.edu/stgs/pdfs/BOYER-%20GCEP%20SGS%20rev2%20oct%2008.pdf., respectively.

[553] A. Panasyuk et al., "Tripartite Enrichment Project: Safeguards at Enrichment Plants Equipped with Russian Centrifuges."

- check cascade configuration

• **For safeguards objective #2**

- conduct Nuclear Material Accountancy Activities (NMAAs)

• **For safeguards objective #3**

- account total Separative Work Unit (SWU) capacity and consumption during inspections
- check identity numbers of cylinders
- check cascade configuration
- confirm that only declared cylinders are attached at feed and withdrawal stations

More detailed safeguards tasks were proposed by the Los Alamos National Laboratory (1995) in the Safeguards Options Study (1995). Table 10.5 shows these verification needs and possible measures that can be employed by the IAEA.

Table 10.5 Safeguards Tasks to Achieve Specific Safeguards Objectives[554]

Objectives	Needs
#1	• Continuous monitoring to verify that HEU has not been produced since the last inspection • In-line monitors to verify UF_6 in header pipes • Environmental sampling in and near the plant • Verification of cascade configuration changes
#2 and #3	• Verification of UF_6 • Design Information Verification procedures for operating facilities
#3	• (Continuous) Verification of SWU consumption, i.e., SWU monitoring[555]
	• (Continuous) Verification of plant throughput

10.4.4 Safeguards Approach

A. Features of GCEPs

Developing safeguards approaches is the process of setting the conditions or environments conducive to conducting effective and efficient inspections. One might think that the development of safeguards

[554]E.A. Hakkila et al., *The Safeguards Options Study.*, pp.102-105. This report uses the term, verification needs. The author interprets the terms as safeguards tasks.

[555]A. Panasyuk et al., "Tripartite Enrichment Project: Safeguards at Enrichment Plants Equipped with Russian Centrifuges." The introduction of SWU (separative work) monitoring was proposed as a means to confirm the actual production of the plant, and thereby provide a means to assure that the entire production capacity is used to produce declared product. Three methods are under consideration for SWU monitoring in terms of frequency and tools: (i) annually, in conjunction with closing the material balance; (ii) monthly, on the basis of verified transfers of inputs and outputs through cylinder verification; and (iii) monthly, on the basis of the flow monitors and CEMOs. However, the introduction of SWU monitoring for actual inspections seems to be infeasible.

approaches for GCEPs is straightforward. In reality, it is very complex because security, economic, and technical issues are entangled. Security issues are mainly related to the protection of sensitive enrichment technologies from proliferation; there are also concerns about protecting commercially sensitive (proprietary) information. Economic issues are connected to the effective operation of uranium enrichment facilities, avoiding the frequent intrusion by inspection activities. A high degree of flexibility and efficiency in the operation of GCEP also complicates the establishment of straightforward safeguards procedures.[556] Furthermore, the use of different designs for GCET, such as Russian, URENCO, American, and Pakistani designs, makes it much harder to establish universal safeguards measures for GCEPs.

B. Inspection Regimes

Unique features of IAEA safeguards at GCEPs can be highlighted by Limited Frequency Unannounced Access (LFUA). At URENCO plants five types of safeguards inspections are carried out: monthly Interim Inventory Verifications (IIVs), annual Physical Inventory Verification (PIV), Design Inventory Verification (DIV), Limited Frequency Unannounced Access (LFUA), and Complementary Access (CA). These are shown in Table 10.6.[557] Each inspection has different objectives and different frequency. LFUA is a unique inspection regime, which is applied to only GCEPs.

Table 10.6 Inspections Currently Applied to URENCO Plants

Types	Objective	Frequency
Interim Inventory Verification	To verify material flow	11 times per year [a]
Physical Inventory Verification	To verify physical inventory	Annually
Design Inventory Verification	To verify that the plants are built in line with the design information	As necessary [b]
Limited Frequency Unannounced Access	To detect undeclared HEU production "inside cascade halls"	4-12 times per year [c]
Complementary Access	To resolve questions or inconsistencies	As necessary

Notes
[a] The HSP suggested that the average frequencies of routine inspection visits can be 12-15 times per year for outside cascade halls.[558]
[b] DIVs are carried out once on a new plant is built and repeated up to once a year thereafter.
[c] However, depending on the size of the GCEP, it may vary from four to twelve times per year [W. Fisher and G. Stein (1999)] or from four to ten times per year [B.D. Boyer (2008)].

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556 Glaser, "Beyond A. Q. Khan: The Gas Centrifuge, Nuclear Proliferation, and the NPT Regime.", pp.1-5.
557 Friend, "Urenco's Views on International Safeguards Inspection".
558 Boyer, *Safeguards Approaches for Gas Centrifuge Enrichment Plants: LANL Safeguards Systems Course - Pilot 2008.*

C. Limited Frequency Unannounced Access (LFUA)

LFUA was proposed to resolve conflicting issues about the application of safeguards at GCEPs between facility operators and safeguaders. Safeguarders need information to be as detailed as possible in order to meet safeguards demands. On the contrary, facility operators want to protect sensitive technology embedded inside cascade hall areas. They have the right to establish restricted areas so that IAEA inspectors are not given access to the areas according to INFCIRC/153.[559] Even the IAEA prefers to keep its own inspectors away from proliferation-relevant technology because IAEA inspectors represent the IAEA for a limited time.[560] Once they complete their duties, they go back to home countries and may contribute to nuclear programs. Therefore, the application of safeguards to GCEPs should be always a balanced task between accomplishing safeguards objectives and avoiding unnecessary information acquisition. In this regard, the most critical and complex issue is the degree of the inspectors' accessibility inside cascade hall areas.

During the HSP study, an evaluation group proposed a partial solution by comparing the results of the safeguards models "without inspector access to the cascade hall" and" with inspector access to the cascade hall." The evaluation group recommended so-called "***Limited Frequency Unannounced Access (LFUA)***" as the optimum solution.[561] Finally, the HSP accepted LFUA and containment and surveillance system for a safeguards inspection scheme inside the cascade hall.

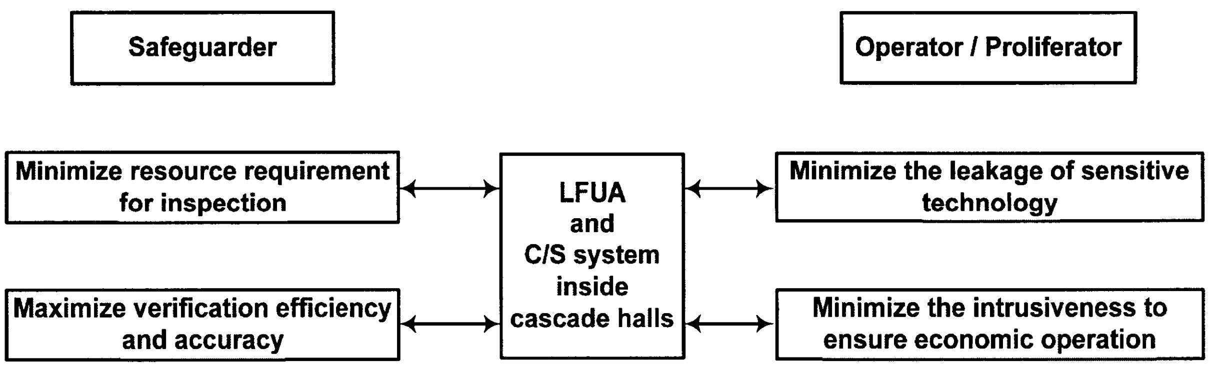

Figure 10.2 Different Positions for Safeguards Measures inside the Cascade Halls

The LFUA enables the inspector to have unannounced access to the cascade hall, specified in terms of time and space. The inspectorates are given access to the cascade halls within two hours, either

[559] Paragraph 46, (b), (iv). "If the State so requests, a special material balance area around a process step involving commercially sensitive information may be established."
[560] Paragraph 9 (Agency Inspectors) of INFCIRC/153. "The visits and activities of Agency inspectors....as well as to ensure protection of industrial secrets or any other confidential information coming to the inspectors' knowledge."
[561] Fischer and Stein, "On-Site Inspections: Experience from Nuclear Safeguarding.", pp.45-54.

during the course of an announced routine inspection or on a completely unannounced, random basis [562] with the frequency of 4-12 times per year. The duration of LFUA is between one and eight hours, depending on whether the inspector only makes visual inspections or also performs measurements.[563] The LFUA provides the benefit of unpredictability and increases the efficiency of safeguards.

D. Short Notice Random Inspection (SNRI) to GCEPs[564]

SNRI is the concept of inspections that are performed at randomly chosen times at short notice. The SNRI/Mailbox approach was first introduced in 1984 by Gordon and Sanborn specifically for IAEA safeguards application at the Portsmouth GCEP. But the concept was not applied because the plant was canceled before the concept was implemented. The concept was then adopted by the IAEA plant for initial application at LEU Fuel Fabrication Plants (FFP) or Uranium Conversion Facilities (UCFs) in the early 1990s.[565] The first field-test of SNRI was conducted at U.S. Westinghouse LEU FFP from March to August 1993. The test demonstrated the validity, technical feasibility, and the effectiveness of SNRI.[566] The SNRI/Mailbox approach was used during the HEU downblending verification experiment at the PGDP during 1997-1998.[567] However, the plant as a whole was not subject to the approach, and the experiment was completed in 1998.[568] The plant is not at present subject to the approach. SNRI was also introduced in 1998 in Japan and currently. All LEU FFPs and UCFs in Japan are now subject to SNRI.[569] SNRI enables the IAEA to make technically valid statements of verification of shipment or

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562 For LFUA, inspectors should notice GCEP operators at least two hours before an access to cascade halls. This two-hour time window was determined considering the time long enough for the operator to protect proprietary information but not long enough to remove all evidence of illicit activity

563 Fischer and Stein, "On-Site Inspections: Experience from Nuclear Safeguarding."However, Brian Boyer (2008) suggests that LFUA is performed 4-12 times per year for facilities with less than 1000 MT SWU/yr.

564 M. M. Curtis and P. Durst, "An Inspector's Assessment of the New Model Safeguards Approach for Enrichment Plants," (Pacific Northwest National Laboratory, July 2007).

565 Leslie Fishbone et al., "The Mailbox for Randomized Safeguards Inspections" (paper presented at the Proceedings of the 13th ESARDA Symposium on Safeguards and Nuclear Material Management, 1991)., pp.83-86; Leslie Fishbone, "Field Test of Short-Notice Random Inspections for Inventory - Change Verification at a Low-Enriched-Uranium Fuel Fabrication Plant," (Upton, NY: Brookhaven National Laboratory, April 1995).

566 Fishbone, "Field Test of Short-Notice Random Inspections for Inventory - Change Verification at a Low-Enriched-Uranium Fuel Fabrication Plant."; I. Tsvetkov et al., "Implementation of Short Notice Random Inspection (SNRI) at Japanese Low Enriched Uranium (LEU) Bulk Facilities - the Experience Gained and an Inspectorate Perspective," (2005).

567 David Gordon et al., "BNL-65714."The IAEA performed its Design Information Verification (DIV) during December 1-17, 1997.

568 P. L. Kerr et al., "IAEA Verification Experiment at the Portsmouth Gaseous Diffusion Plant: Report on the Cascade Header Enrichment Monitor, LA-13557-MS." Between December 12, 1997 and October 8, 1998, LANL and IAEA personnel conducted a verification experiment at the Portsmouth Gaseous Diffusion Plant.

569 I. Tsvetkov et al., "Implementation of Short Notice Random Inspection (SNRI) at Japanese Low Enriched Uranium (LEU) Bulk Facilities - the Experience Gained and an Inspectorate Perspective."

receipt strata in the absence of a resident inspector.[570] SNRI effectively verifies a complete flow of nuclear materials without increasing inspection frequency and resources.[571]

The principal objective of SNRI is to allow complete flow verification coverage of the transfers of safeguarded material between facilities by randomizing the time of inspections and projecting the verification data from collected samples over the material balance period. Additional objectives of the SNRI can include:

- The confirmation of consistency between the plant operation and the declared operation program and the state's fuel cycle;
- The deterrence of data falsification by shortening the interval between the notice of the inspection and the granted access; and
- More efficient and cost-effective verification of material flow in process and in transfer. [572]

The effectiveness of SNRI is dependent on inspectorate resources level, operational program of the particular facility, fixed sample size process, and travel conditions to the target facilities. SNRI can detect diversion activities with the IAEA desired detection probability.[573]

E. Nuclear Material Accountancy (NMA)

Nuclear Material Accountancy (NMA) is performed at three levels: the nuclear material accounting activities at facility level by facility operators; the State System of Accounting for and Control of nuclear material (SSAC) activities at the state authority level; and evaluation activities at the IAEA level. This section focuses on Nuclear Material Accounting Activities (NMAA). NMAA is designed to establish the quantities of nuclear material within defined areas and the changes in those quantities within defined periods.[574] NMAA includes establishment of Material Balance Areas (MBAs), record keeping, nuclear material measurement, preparation and submission of accounting reports,[575] and verification of the correctness of the nuclear material accounting information. The IAEA concludes its NMA by comparing the operator's declarations and inspection data obtained during NMAA.

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570 W. Murphey, C. Emeigh, and L. Lessler, "Some Remarks Relating to Short Notice Random Inspection (SNRI) and Verification of Flow Strata" (paper presented at the Annual Meetings of International Nuclear Materials Management New Orleans, LA, July 28-31 1991).

571 I. Tsvetkov et al., "Implementation of Short Notice Random Inspection (SNRI) at Japanese Low Enriched Uranium (LEU) Bulk Facilities - the Experience Gained and an Inspectorate Perspective."

572 Ibid.

573 Ibid.; J. Huenefeld et al., "Implementation of Short Notice Random Inspection (SNRI) at Japanese Low Enriched Uranium (LEU) Bulk Facilities - the Experience Gained and an Inspectorate Perspective," (2005).

574 IAEA, *IAEA Safeguards Glossary 2001 Edition.*, p.46.

575 David M. Gordon and Jonathan B. Sanborn, "An Approach to IAEA Material-Balance Verification with Intermittent Inspection at the Portsmouth Gas Centrifuge Enrichment Plant," (Upton, New York: Brookhaven National Laboratory, 1984). Accounting ledgers at GCEPs include Shipping forms, material transaction reports and journals, transfer receipts, process sample reports, weight tickets, process inventory-taking reports, material balance reports, and others. (UF_6 in cylinders)

A GCEP can be divided into several Material Balance Areas (MBAs) in order to facilitate nuclear material accounting. For example, MBAs of a GCEP can be either (i) shipper/receiver MBA, UF_6 handling MBA, and cascade MBA or (ii) storage MBA and Process MBA as shown in Figure 10.3, which shows an overall schematic of a URENCO design-based GCEP.[576]

The flow of nuclear material at a GCEP is as follows. Uranium feeds (UF_6) are provided in cylinders at the receipt/shipment area. The cylinders are weighed in order to verify correctness and then evaluate shipper-receiver differences, if any. They would be stored at a storage MBA until they are introduced into process MBA for enrichment operation. Then, the UF_6 is enriched to the degree which the facility operator wants inside the cascade hall. Once the enrichment operation is complete, enriched UF_6 and by-products (depleted UF_6 or tails) are produced. Both products and tails are stored together with feed cylinders in a storage MBA.

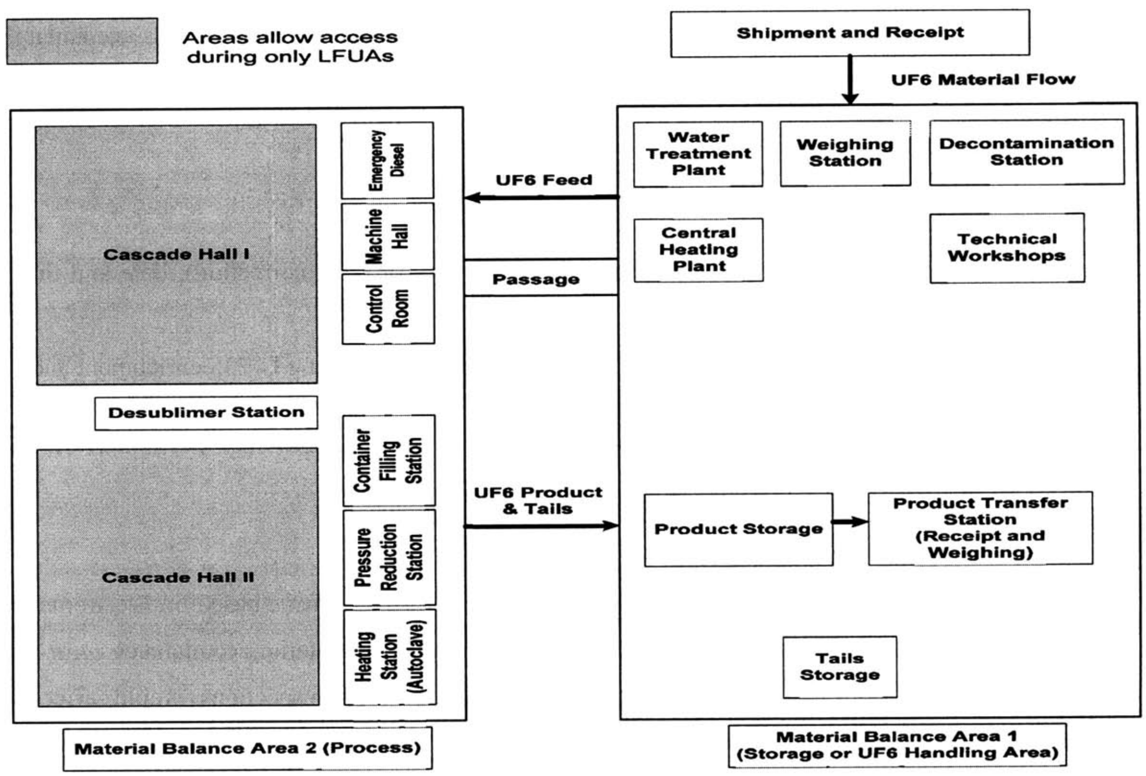

Figure 10.3 Simplified Schematic of Gas Centrifuge Plants[577]

[576] For more information about numerical material balance accounting by the facility operator, see David M. Gordon and Jonathan B. Sanborn, "International Safeguards at the Feed and Withdrawal Area of a Gas Centrifuge Enrichment Plant" (paper presented at the American Nuclear Society Conference on Measurement Technology for Safeguards and Materials Control, Kiawah Island, Charleston, SC, November 26-29 1979).; and see Paragraph 46.(b) of INFCIRC/153 (Corrected)

[577] Cynthia E. Atkins-Duffin, *Nuclear Nonproliferation* (Lawrence Livermore National Laboratory, 2008 [cited May 15 2009]); available from http://www.cresp.org/NuclearChemCourse/presentations/17_Atkins-Duffin_D1097_Atkins-Duffin.pdf.

F. Mailbox System

A mailbox system is shorthand for a computer network or other arrangement in which operators provide operational information in a form that cannot be changed, i.e., a secure tamper-resistant computer. Under a mailbox approach, the operator agrees to hold receipts and shipments for a specified period of time (called the "residence time"), along with a specified number of annual inspections, to enable inspector access to a statistically large enough population of UF6 cylinders and fuel assemblies to achieve the desired detection probability. [578]

The concept of mailbox was first introduced as a form of near real-time material accountancy to complement the SNRI objectives as a potential IAEA safeguards application at the Portsmouth GCEP in 1984.[579] The mailbox declarations have been used for material balance verification by checking the receipts, production, and shipments at some bulk-handling facilities such as LEU Fuel Fabrication Plants (FFPs).

The operator declares the status of his plant to the IAEA on a daily basis using a secure "mailbox" system. These declarations probably should be made by the nuclear-materials accountability staff so the values can be checked for completeness and correctness. The data to be put into mailbox includes:[580]

- Information on the facility status
- A type of event (cylinder connection and disconnection, or error correction), date and time of event, concise note for explanations,
- Accountability values for feed, product, and tails cylinders (including U-235 enrichment and UF_6 purity)
- SWU comparison.
- Cylinder inventory with receipts and shipments of UF_6 cylinders

The IAEA is currently developing a near real-time mailbox reporting scheme based on Electronic Data Transmission System (EDTS). As the operator enters data regarding material accountancy ***on a near-real-time basis*** into the "Mailbox" computer, the randomness of inspections would effectively increase.[581]

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[578] 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," (Upton, NY: Brookhaven National Laboratory, 2006).

[579] Gordon and Sanborn, "An Approach to IAEA Material-Balance Verification with Intermittent Inspection at the Portsmouth Gas Centrifuge Enrichment Plant."

[580] David Gordon et al., "BNL-65714.", David M. Gordon et al., "IAEA Verification Experiment at the Portsmouth Gaseous Diffusion Plant," (August 1998).

[581] For more concepts about randomization, see Fishbone et al., "The Mailbox for Randomized Safeguards Inspections".

G. Concurrent Use of SNRI and Mailbox

SNRI and the mailbox approach can be used in a combined way. The inspectors can access the "Mailbox" during SNRIs and then verify the operator's declarations for that day. This approach will be very efficient in preventing a so-called a "***crash through approach***"[582] to divert nuclear material.

Gordon and Sanborn (1984)[583] and Nishimura (2004)[584] developed the methods of calculating detection probabilities based on the SNRI/Mailbox approach. In both cases, the number of inspections per year is critical in the increase in detection probability. The new IAEA safeguards approach for GCEPs includes the SRNI/Mailbox as one of the tools that can be applied, depending upon the facility and the IAEA evaluations performed in its state level approach. Under current daily reporting schemes (not near-real time), randomization conditions must be met for the valid application of SNRI/mailbox inspection regime. A plant operator would declare the contents and amounts of nuclear material items involved in transfers before knowing the occurrence of SNRI to verify them. [585]

Brookhaven National Laboratory proposed the application of an expanded mailbox concept to GCEPs combined with SNRIs and video surveillance.[586] By adding a video surveillance declaration and verification of UF6 cylinder operational data, the effectiveness and efficiency of safeguards approaches to GCEPs will increase. Once the concept of SNRI/Mailbox system is adopted, this will replace monthly interim inspections (a part of routine inspections). In addition, LFUA can be conducted during SNRI, simultaneously. [587]

H. Nuclear Real Time Accountancy (NRTA)

The IAEA is developing the concept of NRTA as a form of NMA for bulk handling nuclear facilities. If NRTA is fully developed, the IAEA can receive the information about itemized inventory and inventory change data maintained by the facility operators on a near real-time basis.[588] For example, Short Notice Random Inspection (SNRI) and mailbox concepts have been used for increasing the effectiveness and efficiency of safeguards through increasing the unpredictability of inspections at Fuel Fabrication Plants (FFPs). However, these are not common features of current practice at GCEPs. The launch of this

[582] Under this scenario a proliferator simply take the material from its safeguarded storage area as soon as the IAEA inspector had finished performing one inspection. This would be intended to produce HEU before the next inspection falls due. Bragin, Carlson, and Leslie, "Building Proliferation-Resistance into the Nuclear Fuel Cycle".
[583] Gordon and Sanborn, "An Approach to IAEA Material-Balance Verification with Intermittent Inspection at the Portsmouth Gas Centrifuge Enrichment Plant."
[584] H. Nishimura, "Frequency of SNRIs and a Sampling Plant at an SNRI," (Japan: Nuclear Fuel Industries, Ltd., Feb 2004).
[585] Fishbone, "Field Test of Short-Notice Random Inspections for Inventory - Change Verification at a Low-Enriched-Uranium Fuel Fabrication Plant."
[586] Boyer, Gordon, and Jo, "Use of Mailbox Approach, Video Surveillance, and Short-Notice Random Inspections to Enhance Detection of Undeclared LEU Production at Gas Centrifuge Enrichment Plants."
[587] Ibid.
[588] IAEA, *IAEA Safeguards Glossary 2001 Edition.*, p.46.

approach to GCEPs will significantly increase the unpredictability of inspections and that in turn will complicate the proliferators' tasks for producing HEU.

10.4.5 Techniques for Inspection

Inspection techniques that can be used for GCEPs can be grouped into five categories as shown in Table 10.7.

Table 10.7 Inspection Techniques Currently Employed

Techniques	Purpose
Mass measurement	Load Cell Based Weighing System (LCBS) measures UF_6 cylinders.
UER measurement	Non-destructive Assay (NDA) including Cascade Enrichment Monitoring System (CEMO) and Cascade Header Enrichment (CHEM) measures uranium enrichment ratio of UF_6 in feed, product, and tails of cylinders.[a] [589]
	Destructive Assay (DA)[590] for nuclear material accountancy is performed on bulk samples of the nuclear material. [b]
Containment	Tamper-indicating seals verify that no changes are made between inspections.
Surveillance	Video Surveillance (V/S) system can monitor facilities and maintain the continuity of knowledge and can be installed at UF_6 cylinder handling areas, including cylinder Feed / Withdrawal (F/W) stations.[591]
Unattended and remote monitoring	Combinative use of CEMO and Electronic Data Transmission System (EDTS) enables the IAEA to monitor the facility without residence inspectors at a remote distance.

Notes
[a] As reviewed in chapter 7, High-Purity Germanium (HPGe) detectors or NaI scintillator/phototube detectors are used to measure the intensity of 185.7 keV gamma ray from U-235 taking into account the thickness of the cylinder wall. The thickness of the cylinder wall is measured using an ultrasonic thickness gauge.
[b] Typically, a few grams of UF6 are collected in sample tubes from the UF6 cylinders.

10.4.6 Inspection Procedures for Achieving Specific Safeguards Objective

The IAEA needs to verify two factors for achieving its specific safeguards objectives for GCEPs: (a) the verification of the feed, product, and tails UF6 flows at GCEPs during the course of the annual PIV and the monthly IIVs; and (b) the verification of the inventories of UF6 during the PIV. In principle, the

[589] Sharikov, "Verification Challenges for Safeguarding Uranium Enrichment Plants."
[590] Bush et al., "IAEA Experience with Environmental Sampling at Gas Centrifuge Enrichment Plants in the European Union."
[591] McGinnis et al., "Gas Centrifuge Enrichment Facilities in the United States - IAEA Safeguards Implementation".

IAEA performs gross-, partial-, and bias-defect[592] tests that are intended to achieve a 50 percent probability for detection of nuclear material quantities exceeding 75 kg U-235 (i.e., significant quantity) [See Appendix G]. However, in practice the IAEA can achieve its specific safeguards objectives by checking the weight of UF6 and the UER of UF6 as shown in Table 10.8.

Table 10.8 Tests Performed for Achieving Specific Safeguards Objectives

Test	Defect tests	Procedures
UF6 weight	Gross	The IAEA rarely uses this test. However, the so-called "acoustic resonance test" may be used.
	Partial and bias	The IAEA performs the partial- and bias-defect tests for UF6 weight by weighing the declared cylinder on an IAEA LCBS or on an operator's scale that the IAEA has properly authenticated.
UF6 UER	Partial	The IAEA uses gamma-ray NDA, making use of the ***enrichment principle*** through either through LRGS or HRGS. [a]
	Bias	The IAEA obtains a physical sample of UF6 from a declared cylinder so that it can perform the test by using mass spectrometry, i.e., DA.

Note: [a] The IAEA has experienced a number of difficulties with gamma-ray NDA due to cold weather and to the presence of heels with their accompanying decay products, particularly for tails and feed cylinders.

10.4.7 Summary of Safeguards Framework

The annual conclusion of safeguards activities is made through comparing the declared data by facility operators out of SSAC and the data obtained during inspection activities. IAEA inspectors need to gather all available information and data to ensure completeness and correctness, including facility operational data and measurement data about material flows and balance. Figures 10.4 and 10.5 show currently available safeguards tools for GCEPs and a hierarchy of safeguards framework for GCEPs, respectively.

[592] Defect refers to a difference between the declared amount of nuclear material and the material actually present. IAEA, *IAEA Safeguards Glossary 2001 Edition*. page 63.

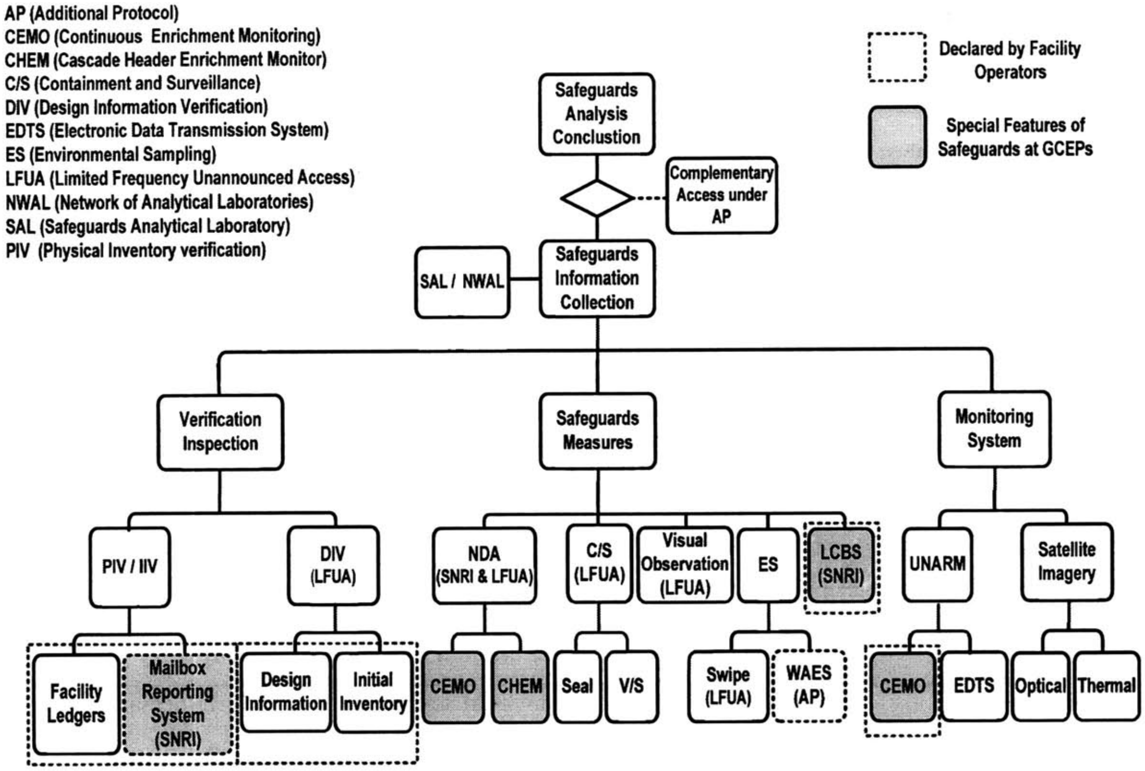

Figure 10.4 Schematic of Safeguards Application to GCEPs

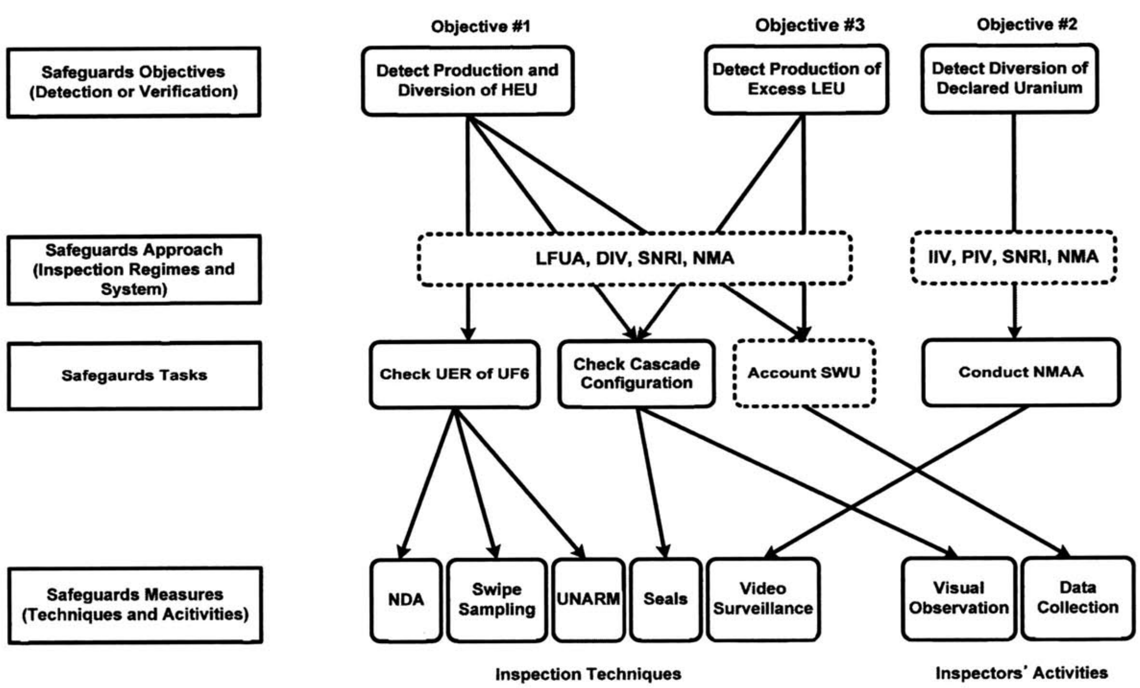

Figure 10.5 Hierarchy of Safeguards Framework for GCEPs[593]

593 SWU balances are hard to use as a detection mechanism, since the operator can easily and credibly understate by substantial amounts (~20%) the separative capacity of his centrifuges. It is not possible to tell the SWU capacity by visual and aural observation.

10. 5 Application of Safeguards Framework

10.5.1 Safeguards Approach: NMA and LFUA

Different safeguards objectives are applied for two district areas, inside the cascade hall and outside cascade hall. The safeguards objective #1 is met primarily inside the cascade hall, while #2 and #3 are met primarily outside the cascade hall. Because of the different features of the two areas, the NMA approach is applied outside, whereas LFUA approach is applied inside. With different safeguards objectives and different safeguards approaches, different sets of framework are also applied.

10.5.2 Safeguards Tasks and Measures Outside the Cascade Hall

A safeguards task of inspectors outside the cascade hall is to verify nuclear material flows and balance through Nuclear Material Accountancy (NMA). Inspectors carry out NMAA during monthly Interim Inventory Verification (IIV) and annual Physical Inventory Verification (PIV) inspections. A key item of information on nuclear material accounting at GCEPs is the total quantity of uranium hexafluoride (UF_6) per U-235 enrichment level. Thus, nuclear material accounting is performed in a way that all characteristics of UF_6 in feed, product, and tails cylinders are detailed in itemized lists.

In order to conclude NMAA as correct and complete, the data declared by the operators and the data obtained by inspectors should be in agreement. The acquisition of data by inspectors can be done in three ways: by collecting facility records such as operating parameters and the shipments/ receipts of UF_6; by reviewing records and reports declared by facility operators; and by measuring nuclear material during inspections. In addition, Video Surveillance (V/S) can be installed for maintaining the continuity of knowledge at Feed/Withdrawal (F/W) stations (or at sublimation/desublimation stations) and cascade hall entry and exit points.[594]

10.5.3 Safeguards Tasks and Measures Inside the Cascade Hall

A task of inspectors inside the cascade hall is to detect the production of uranium at an enrichment level which is higher than declared. This task can be approached via LFUA. As mentioned earlier, five elements of safeguards measures can be applied and detailed descriptions are shown in Table 10.9. Therefore, inspectors' visual observation of the details of enrichment equipment specification s and access to critical plant operating parameters are prohibited, so as to protect proprietary information.

[594] McGinnis et al., "Gas Centrifuge Enrichment Facilities in the United States - IAEA Safeguards Implementation".

Table 10.9 Safeguards Measures inside Cascade Hall [Swindle (1990) and Boyer (2008)]

Safeguards measures	What to inspect or verify?
Seals	Valves in process piping, flanges, inspection equipment left unattended during non-inspection periods
Visual Observation	• **Cascade configuration** Check overall configuration of cascades [a] • **Process piping/flanges** Check at randomly selected locations for comparison with the declared piping drawings Volume measurement of the entire piping system [b] • **Equipment** Verify that no unreported equipment is placed inside cascade halls • **Cylinders** Verify that no unidentified or unreported cylinders are placed inside cascade halls • **Valves in cascades** Check a pressure and a vacuum to confirm that all boundary valves have been placed in the closed position
NDA Measurements	UF_6 contained in the piping, cascade header pipe connections [c], chemical traps, F/W connections points
Swipe Sampling	UF_6 in the piping, [d]surfaces of carts, sampling stations, ventilation filters.
Monitoring	Continuous Enrichment Monitoring system (CEMO)[e] [595]

Notes
[a] 3DLR and GPR can be used.
[b] A measured value is compared with the engineering calculated volume of the entire uranium feed piping system.
[c] Cascade Header Enrichment Monitor (CHEM)
[d] This is very rarely performed.
[e] The result is displayed only qualitatively, as HEU Yes or No, due to operator sensitivity to enrichment level. [Sharikov (2007)]

10.5.4. Compilation of Material and Operation Data

The most accurate way to account for nuclear material seems to be the coupling of the data for nuclear material accounting with that of operational parameters using Separative Work Units (SWUs). In this regard, the monitoring of Separative Work Units (SWUs) was experimented at the Tripartite Enrichment Project (TEP). This is based on the fact that safeguarders can track how facility operators used SWU for enrichment operation. But it turned out to be too complex to apply because of the

[595] Boyer, *Safeguards Approaches for Gas Centrifuge Enrichment Plants: LANL Safeguards Systems Course - Pilot 2008*. The CHEM is applied only at Capenhurst, U.K.; Friend, "Urenco's Views on International Safeguards Inspection".; IAEA, "IAEA Annual Report 2006," (Vienna, Austria: 2006)., p.68. Two flow and enrichment monitors were installed at the Shaanxi GCEP for unattended monitoring of enrichment levels and the quantity of the product.

inherent complexity of SWU calculations as well as systematic and statistical uncertainties. Examples of those uncertainties include errors in association with the measurement of UER and random selection of items on the inventory list.

10.6 Identification of Problems for GCEP Safeguards

Safeguards challenges with regard to GCEPs can be categorized into three issues. These three issues have already been recognized by the IAEA, but the importance of putting more effort into this cannot be over-emphasized. First, the IAEA still needs to enhance the use of inspection techniques in order to detect undeclared proliferation activities with definitive detection probability as shown in Table 10.10. Even though this is not purely the problem of technology development, inspection technique requirements are as follows:

Table 10.10 Requirements for Increasing the Effectiveness of GCEP Safeguards

Objective	Description
#1 HEU production	• Enhanced video surveillance inside cascade halls • Improved timeliness of the analysis of environment samples • Improved NDA measurements on piping inside cascade halls • Instrumentation for flow measurement inside cascade halls such as in-line mass flow meter and thermal mass flow detectors
#2 Diversion of DN/LEU	• Development of installed Instrumentation to quantify the amount of material in-process vessels, usually located in the Feed/Withdrawal area at the time of PIV • Instrumentation for measuring the nuclear material hold-up. [a][596]
#3 Excess LEU production	• Monitoring of UF6 flows at the feed, product, and tails stations -Mailbox/SNRI, video surveillance, -An attended weight monitoring system for each station (authenticated and continuously recording LCBS)

Note: [a] It seems that holdup in the cascade hall may be a problem in the Japanese Plants.

[596] Sharikov, "Verification Challenges for Safeguarding Uranium Enrichment Plants."The measurement of "the nuclear material hold-up" still remains to be one of the principal safeguards challenges in terms of enrichment ratio, the location of material held-up, and the quantity of hold-up.

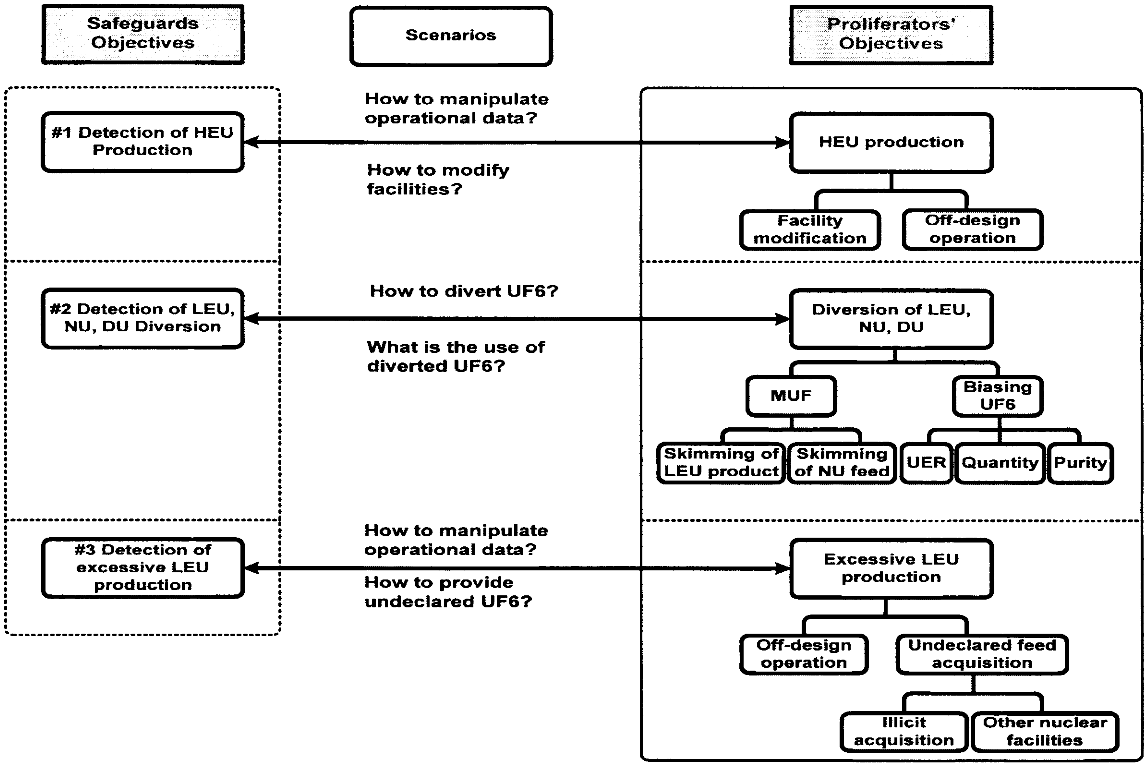

Figure 10.6 IAEA Safeguards Objectives against Plausible Proliferators' Objectives

Second, all safeguards objectives should be reviewed in association with feasible proliferation scenarios including ways to provide undeclared nuclear material and to manipulate operational data. Finally, the current safeguards objectives do not address the issue of the production of HEU at clandestine GCEPs. Figure 10.4 shows the summary of IAEA safeguards objectives for GCEPs under safeguards and corresponding proliferation activities.

10.7 Possible Solutions to Problems of Safeguards for GCEPs

10.7.1 Developing Inspection Techniques

The IAEA continues efforts to circumvent the problem of restricted access inside cascade halls. In April 2005, the IAEA hosted a technical meeting in Vienna to discuss potential detection techniques for the verification of enrichment plants. The IAEA continues to develop techniques to make up for its deficiency with regard to limited access to cascade halls by computerizing safeguards equipment to maximize the use of limited inspection time. The ***three-dimensional Laser Range Finder*** (3DLR) is already being used by the IAEA for DIV activities at the Rokkasho Plutonium Reprocessing Facility (PRF). This system can detect any structural changes within an accuracy of millimeters through comparison of scanned images with previous ones and verify the absence of undeclared structural changes between on-site inspections. The range finder shows changes such as piping arrangements in highlight.[597] However, the software of 3DLR needs further improvement including the revision of 3DLR encryption module.[598] Ground Penetrating Radar (GPR) is a geophysical non-destructive method, and it can detect hidden objects and structures within facilities during regular inspections. GPR is not in use yet. However, GPR also has the potential for DIV and for detecting undeclared facilities.[599] The current challenge of GPR is to interpret the resulting radargrams in an immediate and unequivocal fashion.[600] Also, the IAEA continues efforts to track cylinders inside cascade halls in the absence of inspectors using Centralized Portal Monitor, coupled with RFIDs.[601]

10.7.2 Modeling Efforts (U.S.)

Modeling a safeguards framework application can greatly help to identify loopholes in the framework and to develop proliferation scenarios that can be employed by potential proliferators. Recently, the U.S. decided to construct two GCEPs one at Eunice, New Mexico as a national enrichment facility (by Louisiana Energy Services for 5% U-235) and the other at Piketon, Ohio (by United States Enrichment Cooperation for 10% U-235).[602] The U.S. is developing and evaluating safeguards measures for these new GCEPs. The IAEA has been assessing the needs and capabilities necessary to safeguard GCEPs in an efficient way. As a part of those efforts, the Lawrence Livermore National Laboratory (LLNL), under the auspices of the U.S. Department of Energy (DOE), is developing tools and methods for potential U.S. use in designing and evaluating safeguards systems for GCEPs. One of those products is the LLNL Integrated Safeguards System Analysis Tool (LISSSAT).[603]

Using the LISSAT, the marginal increase of a detection technique's effectiveness can be identified and prioritized given limited resources conditions. Lambert et al. (2007) did some qualitative analysis on the impacts of introducing new safeguards options (safeguard options 2 and 3 in Table 10.10). Their study provides a detection probability for 18 scenarios. These 18 scenarios are plotted according to the combination of three proliferation scenarios and six safeguards scenarios for each proliferation scenario. Safeguards scenarios are schemed considering safeguards options and the feed/withdrawal points (which means whether outside or inside the cascade hall). Table 10.11 shows possible detection probabilities for different scenarios.

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597 Zendel, "IAEA Safeguards Equipment.", pp.72-80.
598 IAEA, "R & D Programme for Nuclear Verification 2008-2009," (2008)., p.48.
599 Ibid., p.31.
600 Zendel, "IAEA Safeguards Equipment."
601 Carlson and Leslie, "Safeguards Intensity as a Function of Safeguards Status".
602 McGinnis et al., "Gas Centrifuge Enrichment Facilities in the United States - IAEA Safeguards Implementation".
603 For more information about diagraph-fault tree methodology, see H. A. Elayat, H. E. Lambert, and W. J. O'Connell, "Systems Analysis of Safeguards Effectiveness in a Uranium Conversion Facility" (paper presented at the 45th Annual Meeting of the Institute of Nuclear Materials Management Orlando, FL, July 18-22 2004).

Table 10.11 Possible Schemes of Safeguards Options [Lambert et al., (2007)]

Safeguards Options (Frequency per year)	IIV	PIV	LFUA	Residence time[b]	SNRI/ Mailbox [c]	V/S [d]	CEMO	LCBS	RFID
	11	1	6	15 days	13				
1	X	X	X	X					
2		X	X	X	X	X	X		
3		X	X	X	X	X	X	X	
4		X	X	X	X	X	X	X	X

Notes
[a] X denotes that a scheme is included in each safeguard option.
[b] Time for holding feed, product, and tails cylinders on average
[c] SNRI replaces IIV and may include LFUA. During SNRI, verification of mailbox declaration, re-Design Information Verification (DIV), Containment Surveillance (C/S) checking can be performed by inspectors.[604]
[d] Continuous and unattended video surveillance

As described in Table 10.11, if the 11 scheduled Interim Inventory Verification (IIV) outside cascade halls were replaced with the Mailbox/SNRI approach, then these SNRIs could also serve as opportunities for LFUA inspections, without increasing the overall number of inspections at the plant. Table 10.12 shows the detection probability for each scenario in Table 10.11.

Table 10.12 Detection Probabilities for Proliferation Scenarios using LISSAT[605]

Scenario	Safeguards 1		Safeguards 2		Safeguards 3	
	Outside cascade	Inside cascade	Outside cascade	Inside cascade	Outside cascade	Inside Cascade
HEU production at declared GCEPs	50-90%		99%		99%	
LEU diversion by skimming	50-90%					
Excessive LEU production with undeclared feed	Below 50%		99%	Below 50%	99%	Below 50%

Note: This table is simplified version of Table 1 from H. Lambert et al [2007].

[604] David Gordon et al., "BNL-65714."
[605] H.Lambert et al., "LISSAT Analysis of a Generic Centrifuge Enrichment Plant" (paper presented at the Proceedings of the 48th annual meetingof the Institute of Nuclear Materials Management INMM, Tucson, AZ, July 8-12, 2007).

10.7.3 Efforts to Standardize GCEPs

Because of the unique features of GCEPs, it is beneficial to reduce degrees of freedom in the construction, operation, and management of GCEPs. For example, URENCO suggests that the IAEA should issue design guidelines for the future construction of GCEPs. The best, but admittedly idealistic scenario would be to use a standard design in building GCEPs so as to facilitate inspection activities. Outside the cascade halls, equipment containing UF_6 including process gas pipework and cylinders, should be ready for inspection. Inside the cascade halls, centrifuge casings and cascade piping should be displayed for easy visual inspection during LFUAs. Minimization of the amount of equipment is also highly recommended.[606]

10.8 Conclusion

This chapter proposed a concept of safeguards framework for GCEPs in order to provide a systematic approach for developing strategies which strengthens IAEA safeguards based on published studies. Despite efforts for strengthening safeguards for GCEPs, it is not expected that the current safeguards can properly deal with the challenges posed by the rapid proliferation of GCEPS. In particular, the unique features of each GCEP make it difficult to strengthen safeguards. In this regard, the establishment of a safeguards framework for GCEPs is particularly important. Such a framework could provide a conceptual structure for safeguards development and application processes. Furthermore, a standardized safeguards framework could be applicable to other types of nuclear facilities.

With regard to a conceptual safeguards framework, the IAEA should put more effort into developing strong, standardized safeguards for GCEPs than for any other type of nuclear facility. Those efforts should include developing inspections techniques, modeling, and standardization. Lessons learned from safeguards for GCEPs will be of great use for Laser Enrichment Technology (LET). LET is the next generation UET and is far more threatening to nuclear nonproliferation than GCET. The establishment of a holistic approach that involves other elements of the NPT regime will be essential to building long-term plans for safeguarding GCEPS.

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[606] Friend, "Urenco's Views on International Safeguards Inspection".

CHAPTER 11 NPT REGIME'S CAPABILITIES FOR DETECTING A CLANDESTINE GCEP

11.1 Introduction

This chapter is devoted to the clear identification of the current status of the NPT regime's capabilities for detecting clandestine nuclear facilities. The current level of technology available for detecting a clandestine GCEP is far from ideal. However, it is still unclear where the NPT regime stands in the process of achieving the desired level of detection technology. Thus, clear differentiation between the current and desired detection ability is extremely important in the Nuclear Nonproliferation Treaty (NPT) regime in order to establish effective strategies in response to proliferation using a GCEP.

The focus of this Chapter is on the technological levels for detecting a clandestine Gas Centrifuge Enrichment Plant (GCEP) with no access. This requires a well-established strategy on the part of the monitoring agency. However, it should be noted that the detection of a clandestine facility itself does not mean that the international community can stop proliferation activities. The use of information regarding detection of a GCEP is limited to only raising reasonable suspicion, which is expected to be followed by inspections on site. Thus, it is highly unlikely that the detection of clandestine UCFs will directly incur political actions by the international community.

11.2 Strategy for Detecting Clandestine Nuclear Facilities

11.2.1 Direct and Indirect Detection

As reviewed in Chapters 6 and 7, a variety of legal and technical measures are available for detecting a clandestine nuclear weapons program in the NPT regime. Each stage of a nuclear weapons program involves different type of proliferation activities and safeguards should consider a different combination of available measures for each stage in the NPT regime. Through these various measures, the IAEA should obtain information about nuclear proliferation activities in a variety of types and from a multiple sources. The collation and analysis of information can contribute to raising the probability of detecting clandestine facilities.

Kemp and Glaser (2007)[607] suggest two ways of detecting clandestine GCEPs and is described in Figure 11.1. First, direct detection approach to a clandestine GCEP can be performed through recognizing environmental signatures. In practice, it is hard to obtain concrete evidence for verifying the existence of clandestine nuclear activities through direct detection only. Thus, indirect detection approach must be employed in order to acquire complementary information. Indirect detection includes

[607] Kemp and Glaser, *The Gas Centrifuge and the Nonproliferation of Nuclear Weapons.*

the detection of auxiliary facilities that support a clandestine facility or the analysis of nuclear trade concerning nuclear-related material and equipment.[608]

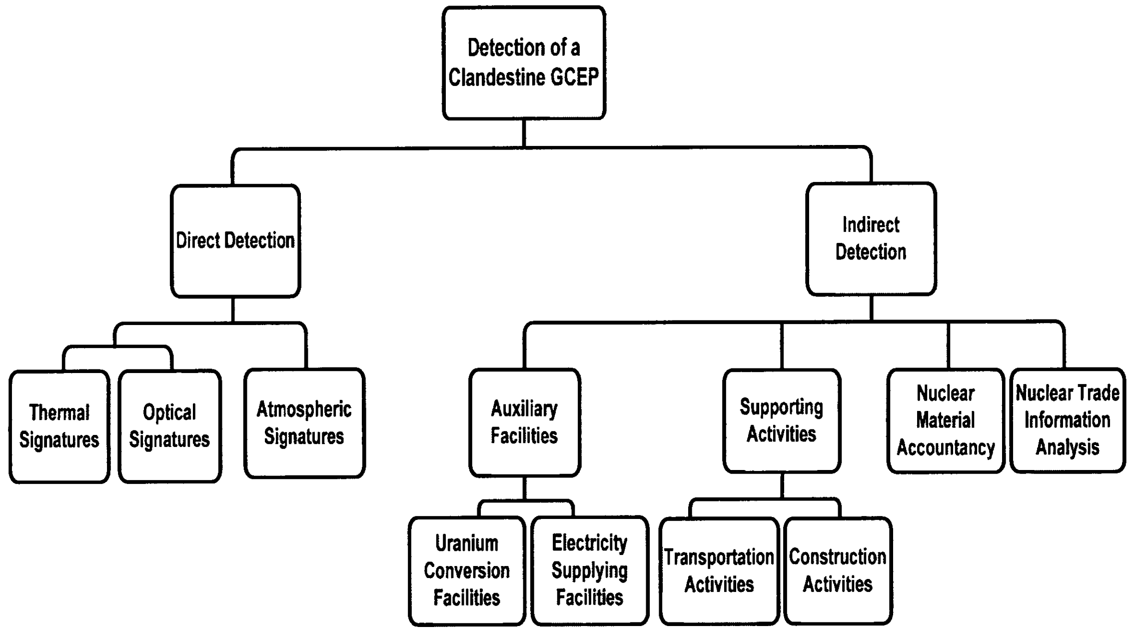

Figure 11.1 Detection Methods for a Clandestine GCEP[609]

11.2.2 Environmental Signatures

Each type of nuclear facility generates its own unique environmental signatures. These environmental signatures can be grouped into optical signatures, thermal signatures, and atmospheric effluents as shown in Table 11.1. The more environmental signatures are available, the higher the probability for detecting the facility. According to the table, nuclear reactors and GDPs generate all of the various types of environmental signatures. On the contrary, UCFs and GCEPs only release gaseous effluents, which make atmospheric detection the only available measure.

[608] Dual-items tracking for gas centrifuge manufacture such as centrifuge motor, frequency converters, aluminum, maraging steel, composite materials.
[609] Kemp and Glaser suggested that the indirect detection of GCEPs by monitoring supporting fuel-cycle facilities may be the most promising route. Kemp and Glaser, *The Gas Centrifuge and the Nonproliferation of Nuclear Weapons*.Kemp and Glaser suggested that the indirect detection of GCEPs by monitoring supporting fuel-cycle facilities may be the most promising route.

Table 11.1 Environmental Signatures of Nuclear Facilities

Classification	Optical signatures	Thermal signatures	Atmospheric effluents
Nuclear Reactors	• Cooling towers or a natural water body • Reactor buildings • Water-vapor plume	•Cooling pond •Hot effluents discharge	Fission gases
Plutonium Reprocessing Facilities (PRFs)	• A very high stack (and shadow) • A long canyon-like building (or with vent) • Ponds or reservoirs for waste or sludge, railroads	Under dispute[610]	Kr-85
Gaseous Diffusion Plants (GDPs)	• Large-area process buildings [b] • Water vapor plume • Cooling towers or a nearby river • Waste management and disposal facilities • Electricity-supplying facilities [c]	•Plumes from cooling towers •Hot roof	HF
Uranium Conversion Facilities (UCFs)	N/A	N/A	UO_2F_2
Gas Centrifuge Enrichment Plants (GCEPs)	N/A	N/A (very little) [d]	HF

Notes
[a] Security perimeter, isolated site, railroads, roads are common features of reactors, reprocessing plants, and GDPs.
[b] The roof of most buildings ventilation shafts
[c] A nearby fossil fuel power plant, large electric switchyard
[d] GCEPs do not require special cooling systems. However, the operation of facilities results in a small increase in the roof temperature. Zhang (2001).

11.2.3 Technologies Available for Detecting Clandestine GCEPs

Under the scenario that access to clandestine nuclear facilities is not given or very limited, technologies that can be used for detecting clandestine facilities include satellite imagery, Environmental Sampling over Wide Area (ESWA), Raman-scattering-based LIDAR and Differential Absorption LIDAR (DIAL) as shown in Figure 11.2.[611]

[610] Hui Zhang (2000) argues that PRFs do not emit thermal signatures. Hui Zhang, "Report: Uses of Commercial Satellite Imagery," *The Nonproliferation Review* (Summer 2000). On the contrary, CNS (2003) claims that the United States can detect thermal signatures of PRFs using infrared sensors on satellites. James Martin Center for Nonproliferation Studies (CNS), *NWFZ Clearinghouse*.

[611] The IAEA classifies environmental sampling scheme as swipe sampling, location specific sampling, and Wide Area Environmental Sampling (WAES). Some scholars claim that only WAASG was originally meant to be WAES. In this paper, a new term, Environmental Sampling over Wide Area (ESWA) that includes the second and the third types of environmental sampling is used in order to prevent the confusion of terminology. LIDAR stands for Light Detection and Ranging.

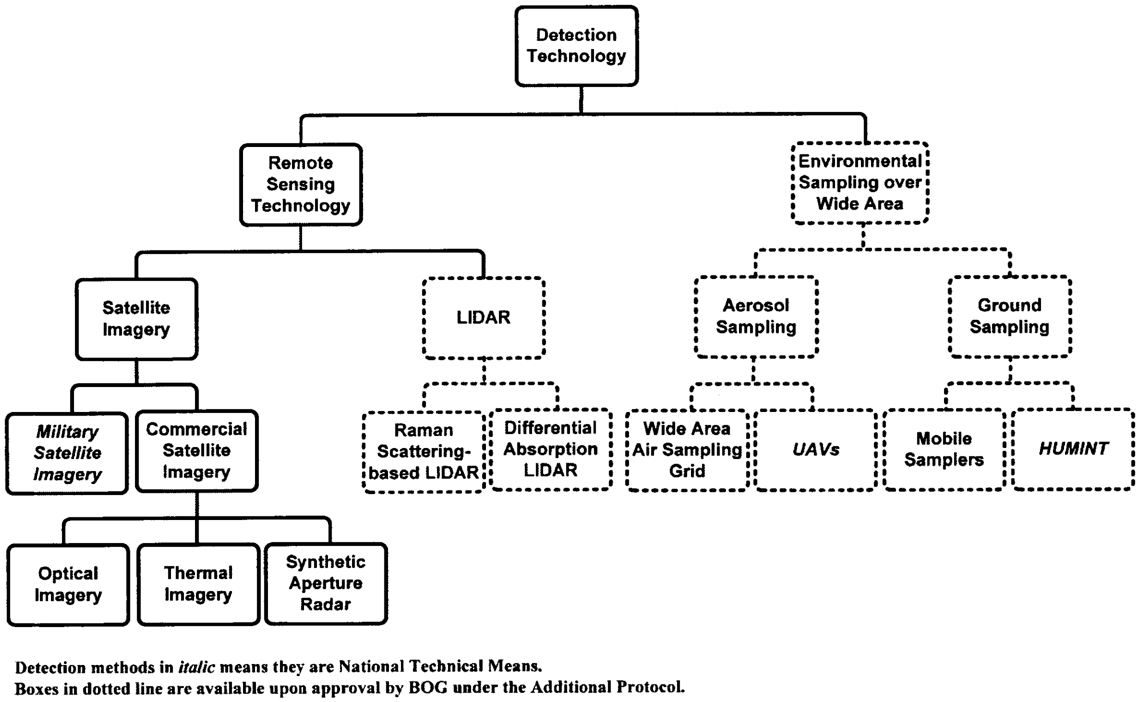

Figure 11.2 Technologies Applicable to Detecting Clandestine GCEPs

The use of detection technologies is not solely the problem of the IAEA's technical capabilities but related to the legal capabilities of the IAEA for two reasons: first, the application of ESWA requires the approval of the Board of Governors (BOG) of the IAEA under the Additional Protocol; second, military satellites, Unmanned Aerial Vehicles (UAVs), and Human Intelligence (HUMINT) assets are part of NTMs which require cooperation with governmental authorities.

11.3 Definition of Detection and Technology Levels

Before beginning discussion about detecting clandestine nuclear facilities, the use of term, detection, should be defined. The IAEA should establish the level required to achieve its safeguards goal. Keeley and Cameron (1998) argue that the IAEA requires a detection capability that would raise sufficient suspicion to justify an inspection rather than a detection capability that would identify definitive evidence.[612] For now, this argument seems reasonable considering the current level and the inherent probabilistic nature of detection technology. Yet, this argument does not consider the inability to get access to a clandestine GCEP within current IAEA capacity such as the case of North Korea and Iran.

[612] Keeley and Cameron, "Chapter Two the Need to Know: Commercial Satellite Imagery and IAEA Safeguards." They argue that raising reasonable suspicion may be needed to justify an inspection request, which seems to be impractical in the current capacity of the IAEA. Concerning the use of the term "definitive," Merriam-Webster defines "definitive" as "serving to provide a final solution or to end a situation." Available from http://www.merriam-webster.com/

In this regard, the IAEA should continue its efforts to achieve the technology level which can obtain definitive evidence.

Three levels of detection technology are proposed as shown in Figure 11.3 and Table 11.2. The differentiation of these three different levels enables the NPT regime to identify the current status of detection technology level and how far the current detection technology level is from that which is desired. A size of the gap between different technology levels depends on the type of technology, the IAEA's available resources, and the level of international cooperation among the international community.

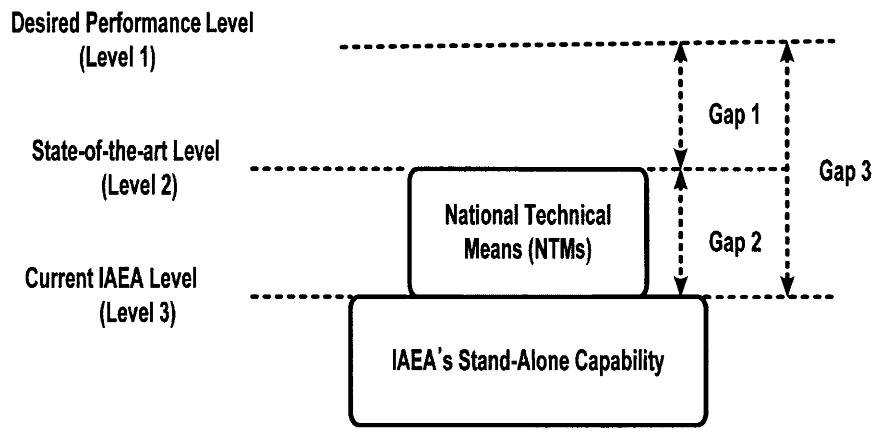

Figure 11.3 Levels of Information and Their Gaps

Table 11.2 Definition of Different Technology Levels

Levels	Definition
Desired performance	This is the highest level of information that can be defined as "the level at which the IAEA can detect proliferation activities with confidence" or is "required level to detect proliferation activities with concrete evidence"[613]
State-of-the-art	This level of information can be obtained through other sources such as National Technical Means (NTMs), [614] the Intelligence Community, and national laboratories in the IAEA's member states.[615] However, exact capabilities from NTMs are generally not known for security reasons.

(Continued)

[613] Personal Communication with Yong-Sang Choi, Sep. 15, 2009. However, the conventional approach is to allow a confidence level between 85 and 99 percents. In satellite imagery analyses, a confidence level is statistically determined by counting how many tests a target pixel has passed.

[614] This is the term that first appeared as national technical means of verification, but was not detailed, in the Strategic Arms Limitation Treaty (SALT) between the US and USSR. The term covers a variety of monitoring technologies, including others used at the time of SALT I. Examples are imaging satellites, imaging aircraft, SIGINT platforms, etc.

[615] National Technological Means (NTMs) including satellite imagery for IMINT, and other technologies for HUMINT are representative of this level of information. Laboratories may belong to this category with the state-of-the-art technology.

Current IAEA	This level of information can be obtained through IAEA's stand-alone capability. The definition of stand-alone capability can be described as "the capability that the IAEA can utilize without any delay or barriers, as necessary." The IAEA has the capability for analyzing commercial satellite imagery, which is done by Satellite Image Analysis Laboratory (SIAL), established in 2000 in the Department of Safeguards.

11.4 Current Capabilities for Detecting Clandestine Nuclear Facilities

The International Panel on Fissile Materials (IPFM) (2007) [616] suggests overall estimates on the NPT regime's technical capabilities for detecting clandestine nuclear facilities as shown in Table 11.3 [See Appendix E].

Table 11.3 Current Capability for Detecting Clandestine Nuclear Facility

Facility	**Satellite imagery [IPFM (2007)]**		**Aerosol ESWA**				
	Visible Near Infrared (VNIR)	**Thermal Infrared (TIR)**	**Long range**	**Short range**	**Atmospheric signatures**	**Capability for signatures**	**Remarks**
Nuclear reactors	Yes	Yes	Yes	Yes	-	-	-
PRFs	No	No	Yes*	Yes	Kr-85	100 km	Field experiment [617]
GDPs	Yes	Yes	No	Possible	UO_2F_2	-	-
UCFs	No	No	Yes*	Yes	UO_2F_2	200-300 km with 1ppb & 400 km with 0.1 ppb	Based on HYSPLIT modeling [618]
GCEPs	No	No	No	No	UO_2F_2	N/A	Gronau facility
Nuclear weapons test	Possible	Possible	Yes	Yes	Xe isotopes (Xe-135, 133m, 133, 131m)[619]	Pending the nuclear yield magnitude	Field experiment

Notes

[a] From a technological point of view, it is generally suggested that many analytical methods in aerosol sampling can achieve 1 to 0.1 ppb sensitivity under limited circumstances.[620]

[b] * means that detection depends upon the capacity of the facility.

[c] No field experimental data is available for UCFs.

[616] Table 9.1 International Panel on Fissile Materials, International Panel on Fissile Materials (IPFM), "Global Fissile Material Report 2007: Second Report of the International Panel on Fissile Materials," (2007).

[617] Kalinowski, "Detection of Clandestine Production of Nuclear-Weapons-Usable Materials."

[618] Wood, Glaser, and Kemp, "The Gas Centrifuge and Nuclear Weapon Proliferation."

[619] Bösenberg and Kalinowski, "Detecting Atmospheric UF6 and HF as Indicators for Uranium Enrichment."

[620] R Scott Kemp, "Technical Note on the Detectability of UO2F2 Aerosols Produced by UF6 Released from Clandestine Uranium Conversion Plants," (July 28, 2006).

Nuclear reactor facilities can be easily detected by both satellite imagery and Environmental Sampling over Wide Area (ESWA), whereas GCEPs can hardly be detected. This fact suggests that indirect ways to detect GCEPs should be developed in order to detect clandestine GCEPs.

11.5 Direct Detection of GCEPs

11.5.1 Environmental Signatures

A. General

Before discussing further details on capabilities of current remote sensing technology, characteristic environmental signatures (by-product effluents and other observables) of GCEPs should be reviewed. In this paper, these signatures are classified into optical signature, thermal signature, atmospheric effluents, and others as shown in Table 11.4. These signatures also can be grouped into operation- or construction-related signatures.

Table 11.4 Environmental Signatures of UEFs

Classification of Signatures	Features		Remarks
Optical signature[621]	Characteristic infrastructure	Security perimeter Enrichment buildings Electricity supply	Operation and construction
	Daily activities	Large trucks and roads for shipment[622]	
Thermal signature	Heat release	Temperature increase of a roof of a facility in association with operation	Operation
Atmospheric effluents	Aerosol particles	Uranyl fluoride (UF_2O_2)	Operation
	Gas	Uranium hexafluoride (UF_6)	
		Hydrogen fluoride (HF)	
Other signatures	Seismic signatures	Explosion of tunnels for underground facilities	Construction
	Electromagnetic signatures[623]	Use of high frequency of electricity for gas centrifuge machines	Operation

621 For information about other types of nuclear facilities, please see Zhang, "IAEA-SM-367/16/01".

622 Shipment of UF6 cylinders, components required for the construction of a GCEP including gas centrifuge machines.

623 The detection of an electromagnetic signature is currently a potential method and is still very limited within a kilometer. Kemp and Glaser, *The Gas Centrifuge and the Nonproliferation of Nuclear Weapons.*; and David E. Sanger and William J. Broad, *How to Listen for the Sound of Plutonium* (New York Times, Jan. 31 2006 [cited Mar. 5 2009]).

B. Atmospheric Signatures

The uranium hexafluoride (UF_6) gas escapes during the various process steps at UEFs. But, UF_6 quickly reacts with atmospheric humidity and produces UF_2O_2 and HF in humid air as follows: [624]

$$UF_{6(g)} + 2H_2O_{(l)} \rightarrow UO_2F_{2(s)} + 4HF_{(g)} \qquad (11.1)$$

Due to such reactivity of UF6, by-products of UF6 should be considered for detecting these atmospheric signatures. However, UF_2O_2 is the only reliable indicator for uranium enrichment operation because this is the only particle that contains uranium and fluorine. There are no natural or other anthropogenic sources for this compound. On the contrary, the detection of HF does not provide concrete evidence for uranium enrichment because it can also be emitted from other industrial facilities other than UEFs.

C. Optical and Thermal Signatures

Very few operating signatures for a GCEP are available for Visible and Near Infrared (VNIR) and Thermal Infra-Red (TIR) Imagery. Optical features include characteristic infrastructures and construction activities. However, unlike a Gaseous Diffusion Plant (GDP), a GCEP does not have obviously observable characteristic features. Thus, these features must be collated with other information.[625] The footprint of a GCEP can be considered as a secondary optical feature. However, these vary with the intent of the proliferators and, in general, are too small to be detected reliably. For example, Glaser (2007) suggests that a GCEP that capable of producing 25 kilograms (kg) of HEU annually, about 6,000 Separative Work Unit (SWU)/yr, is estimated to have a hypothetical footprint of 160 square meters (42 ft x 42 ft).[626] The smallest GCEP that has been identified thus far is the Fuel Enrichment Plant (FEP) at Natanz, Iran with the footprint of 200 m x 200 m, with an estimated capacity of 7,500 SWU per yr (SWU/yr), which can produce 40 kg of HEU. [627]

A GCEP releases less heat than that of a GDP because of higher operating efficiency. The increase in the roof temperature from a GCEP is very small. Jasani (2009) suggests that a reference GCEP of 1,000 (tonSWU/yr) would release 15 MW of heat via roof-mounted air cooled radiators or a low-profile forced draught cooling tower. These signatures, if detected, could be used for further estimates of production capabilities. [See Appendix F]

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[624] iGSE, "iGSE-Detection of Clandestine Production of Nuclear-Weapons-Usable Material.", pp.4-8.
[625] Zhang, "IAEA-SM-367/16/01".
[626] Glaser, *Making Highly Enriched Uranium*, Kemp and Glaser, *The Gas Centrifuge and the Nonproliferation of Nuclear Weapons*.
[627] R. Scott Kemp and A. Glaser, "The Gas Centrifuge and the Nonproliferation of Nuclear Weapons" (paper presented at the Proceedings of the 9th International Workshop on Separation Phenomena in Liquids and Gases, Beijing, Sep. 18-21 2006).

11.5.2 Detecting through Environmental Signatures

A. Detection through Atmospheric Effluents

Table 11.5 shows the characteristics of three atmospheric effluents emitted from a GCEP. The detection limit can be interpreted as the distances in which each atmospheric effluent can be detected. The distances may be divided into right above the stack, short distance from the fence to several km away from the fence, and significant distances.

Table 11.5 Comparison of Atmospheric Signatures [628]

Signatures	Characteristics			
	Phase	Detection Means	Problems for Detection	Detection Limit
UF_6	Gaseous	DIAL	• Highly instable	30 ppmV~ 50 ppbV
HF	Gaseous	DIAL	•Chemically instable •Not specific because of the existence of other industrial facilities that emits HF	100 ~ 0.2 pppV or 0.02 mg/m^3
UF_2O_2	Aerosol Particles	ESWA or LIDAR[629]	•Non-detectable because of extremely low signature	N/A

Note: Detection limit means minimum detectable concentration. These values are estimated using the differential absorption cross section of the gas and the range interval where the gas is present, and the differential optical depth.

Detailed explanation regarding the detectability of atmospheric effluents is as follows: First, UF2O2 is the only atmospheric effluent that can be detected, but the detection limit of GCEPs can be achieved only in the vicinity of the release point. In sum, all of three atmospheric effluents of a GCEP cannot be detected even off the fence of the facility unless accidental release occurs. Second, the amount of HF release to the level of detection limit cannot be achieved with conventional detection technology even right above the exhaust stack because air filters in the exhaust stack can effectively contain HF and significantly decrease the amount of release to the atmosphere. However, the use of DIAL shows a possibility of detecting this gaseous tracer. Third, UF6 is the most difficult signature to

[628]M. Kalinowski, "Nuclear Safeguards and Nonproliferation" (paper presented at the ESARDA Training Course, Ispra, April 14-18 2008).; Bösenberg and Kalinowski, "Detecting Atmospheric UF6 and HF as Indicators for Uranium Enrichment.", pp.55-59.

[629] Bösenberg and Kalinowski, "Detecting Atmospheric UF6 and HF as Indicators for Uranium Enrichment." In particular, Raman scattering-based LIDAR can be applied. Raman spectroscopy is another way to measure a molecule's infrared fingerprint. Here light of high frequency (visible or UV) interacts with the molecule, and re-emitted (scattered) light is analyzed. Due to the Raman effect, some of the scattered light will be shifted in frequency by an amount equal to a characteristic frequency of the molecule. With a single-frequency laser source, the returning light will display a spectrum with bright lines corresponding to molecular frequencies—also a fingerprint.

detect. The amount of UF6 release even right above the exhaust stack is three orders of magnitude below the detection limit of DIAL because UF6 is quickly converted into UF2O2 and HF prior to release (inside the building) or within minutes after the release from facilities.

B. Detection through Satellite Imagery

Satellite imagery is very limited in its capability to detect a GCEP because the features of GCEP (small size, no requirements for cooling towers and high-energy efficiency), make it hard to detect by either optical or thermal imageries.[630] 0.5 to 1 meter spatial resolution of optical imagery can detect infrastructural features of any building. However, a GCEP does not have characteristic features. Thus, even if optical imagery detects a suspicious GCEP, it is unlikely that the imagery can prove whether the facility is a GCEP or not. Zhang (2004) analyzed a small GCEP operated by Pakistan at Kahuta. Zhang estimated that the detection of the facility requires a TIR system that has 20-meter thermal resolution and 0.1°K accuracy. This is beyond current commercial satellite capability.[631] The gap in the detection of GCEPs might be bridged if an environmental sampling method is used is in conjunction with imagery."[632]

11.5.3 Evaluation of Direct Detection Technology

Direct detection of a clandestine GCEP using currently available technology does not seem to be possible. Among the four technologies, only spatial resolution of VNIR imagery has reached the desired performance level. Figure 11.4 summarizes the description of different technology levels for detecting clandestine GCEPs. However, TIR is not applicable to the detection of a clandestine GCEP because its spatial resolution still falls short of the desired goal, whereas thermal sensitivity has sufficient capability. Moreover, significant technological advancement in TIR imagery is not expected to be made within the near future. DIAL may possibly be deployed for detection of hydrogen fluoride (HF) emanated from GCEPs, but only within a short range of several km.

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[630] Adam Bernstein, "Monitoring Large Enrichment Plants Using Thermal Imagery from Commercial Satellites: A Case Study," *Science and Global Security* 9, no. 2 (2001)., pp. 143-163.

[631] The most recent commercial satellite, Landsat 7 of the US launched in 1999, has 60-meter thermal resolution and about 0.5 to 1 Kelvin degree accuracy. Zhang, "Report: Uses of Commercial Satellite Imagery.", pp.120-135.

[632] International Panel on Fissile Materials (IPFM), "Global Fissile Material Report 2007: Second Report of the International Panel on Fissile Materials." , pp. 101.

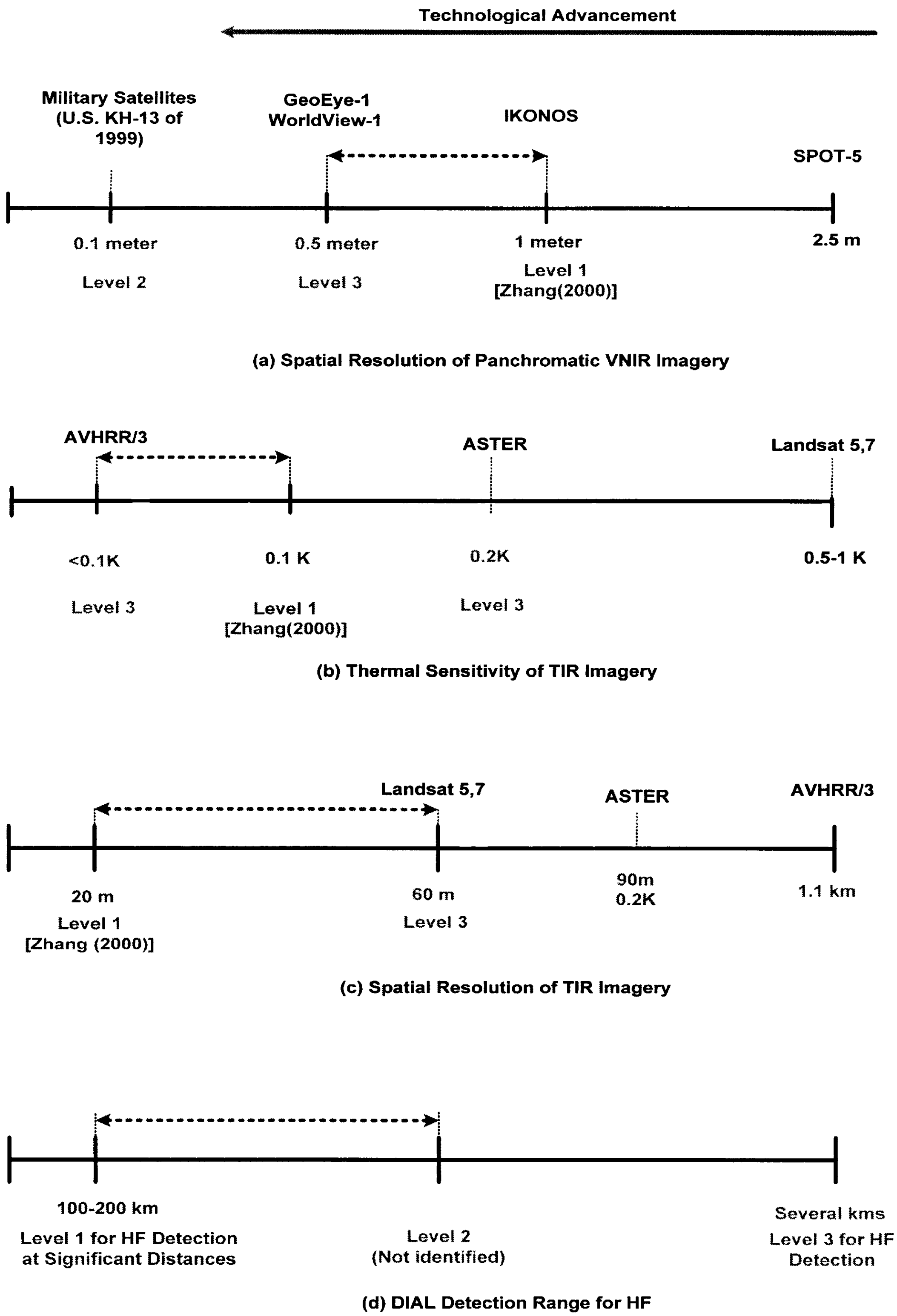

Figure 11.4 Gaps in Technological Levels for Detecting GCEP Using Satellite Imagery and DIAL

11.6 Indirect Detection of Clandestine GCEPs

11.6.1 Detection of Nuclear Facility Construction

The construction of nuclear material production facilities requires activities, such as the shipment of heavy components, and construction work for a considerable period of time. Satellite imagery can provide sufficient capability to detect these activities. Direct detection of clandestine facility construction is very limited and satellite imagery is the only available option. Zhang (2001) estimated that commercial satellites with several days' revisit time and one-meter resolution could detect construction activities of nuclear facilities.[633] However, it may not be feasible for satellite to detect construction activities in the case of small-size or underground facilities.

Nuclear export control measures such as Proliferation Security Initiatives (PSI) and Multilateral Export Control Regimes (MECRs) can complement detection capabilities by satellite imagery. Careful analysis of information about the trade of sensitive Dual-Use Items (DUIs) can be a good indicator for detecting a nuclear weapons program. In the case of the construction of Gas Centrifuge Enrichment Plants (GCEPs), those items include electrical-frequency converters, high-purity cobalt powder for magnetic-top bearing assemblies, high-strength aluminum tubes, and a special grade of steel for rotors, caps, and rotor bearings. Trade information regarding these items by a specific state can be taken as limited evidence for constructing GCEPs.[634]

11.6.2 UCF Operation Detection

It is easier to detect Uranium Conversion Facilities (UCFs) than GCEPs because UCFs release more uranium-containing particles as shown in Table 11.6. The amount of UF_6 that can leak out of a UCF is much more than that which would leak out of a GCEP. UCFs typically release more UF_6 to the atmosphere than GCEPs per unit of throughput because the uranium conversion process occurs at atmospheric pressure, whereas GCEPs operate far below atmospheric pressures. This difference results in a higher probability of detecting UCFs than GCEPs.

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[633] Zhang, "IAEA-SM-367/16/01".

[634] International Institute of Strategic Studies (IISS) observed hundreds of such converters would be required for a production-scale enrichment facility equipped with enough centrifuges to make weapons-grade enriched uranium. Selig S. Harrison, "Did North Korea Cheat?," *Foreign Affairs* 84, no. 1 (Jan/Feb 2005).

Table 11.6 Estimated Uranium Releases from Reference Nuclear Facilities[635]

Type of facility	Maximal (kg/year)	Central (kg/year)	Minimal (kg/year)
Uranium Conversion Facility	10	5	0.2
Gaseous Diffusion Plant	7	4	0.04
Gas Centrifuge Enrichment Plant	2	1	0.01

Note: A reference facility is defined as the facility that produces 25 kg of HEU per year.

11.7 Summary

The current status of safeguarders' technological capabilities for detecting clandestine nuclear facilities focusing on a GCEP was reviewed. Four types of technologies are available for detecting a clandestine GCEP in which inspectors have no access. They are satellite imagery, ESWA, LIDAR, and DIAL. The current level of these technologies seems to be far from the desired performance level because it scarcely releases environmental signatures. It is concluded that among the various types of nuclear facilities, a clandestine GCEP poses the most challenging threat.

There may be several alternative ways to overcome these difficulties. First, all types of information should be fused to raise the probability of detecting clandestine nuclear facilities. Second, satellite Imagery of TIR and VNIR has proven to be effective in locating and characterizing some types of nuclear facilities as well as in monitoring daily activities such as construction and transportation, if this information is accumulated over a long duration. Finally, detecting supporting/auxiliary facilities such as Uranium Conversion Facilities (UCFs) may be helpful in detecting a clandestine GCEP.

[635] Bösenberg and Kalinowski, "Detecting Atmospheric UF6 and HF as Indicators for Uranium Enrichment." cited from D. Albright and L. Barbour, "Source Terms for Uranium Enrichment Plants, Institute for Science and International Security, Compiled for the U.S. Support Program to the IAEA," (Aug. 1997).. This paper remains the only one reference with extensive investigation on uranium releases from GCEPs; A modern UCF that produces enough weapon-grade uranium for making one nuclear explosive device is estimated to release about 20 grams of the 6 tons or so of natural uranium in the UF6 feed. International Panel on Fissile Materials (IPFM), "Global Fissile Material Report 2007: Second Report of the International Panel on Fissile Materials."p.116.

CHAPTER 12 A PROLIFERATOR'S STRATEGY FOR HEU PRODUCTION: PART I

12.1 Introduction

This chapter analyzes possible ways for a proliferator to establish a uranium enrichment program through a Gas Centrifuge Enrichment Plant (GCEP). Most studies on proliferation risk of a GCEP do not provide holistic overview of (a) how a GCEP can be built, regardless of whether they are declared or clandestine, or (b) how uranium can be obtained. In this regard, a flow chart that describes a possible process for completing the production of Highly Enriched Uranium (HEU) was developed. A proliferator's plan for the production of HEU is analyzed according to this flow chart.

This chapter is composed of three parts: i) ways to acquire nuclear elements required for a GCEP program either through transfer or trade, ii) ways to construct a GCEP, and iii) ways to provide uranium feed to a GCEP for producing HEU. For the systematic analysis of the proliferator's strategy to acquire nuclear material, it is important to assess the legitimacy of the methods used in obtaining this material. Such information is necessary if one wants to research improvements to the system of Multilateral Export Control Regimes (MECRs), which were reviewed in chapter 5. Although the discussion is focused on a GCEP, the approach would be applicable to other types of nuclear facilities.[636]

12.2 A Proliferators' Strategy to Prepare a GCEP for Producing HEU

Once a proliferator decides to produce HEU at a GCEP, the proliferator will set up an appropriate plan and try to make the best use of domestic resources and external assistance. As we can see in the cases of Iraq, Iran, and North Korea, proliferators will carefully study the weaknesses of the contemporary non-proliferation regime prior to the initiation of any plan. Based on the analysis of possible ways of acquiring the necessary nuclear elements, a strategy to set up a GCEP for producing HEU can be developed, Figure 12.1.

[636] E.A. Hakkila et al., *The Safeguards Options Study*. p.89.

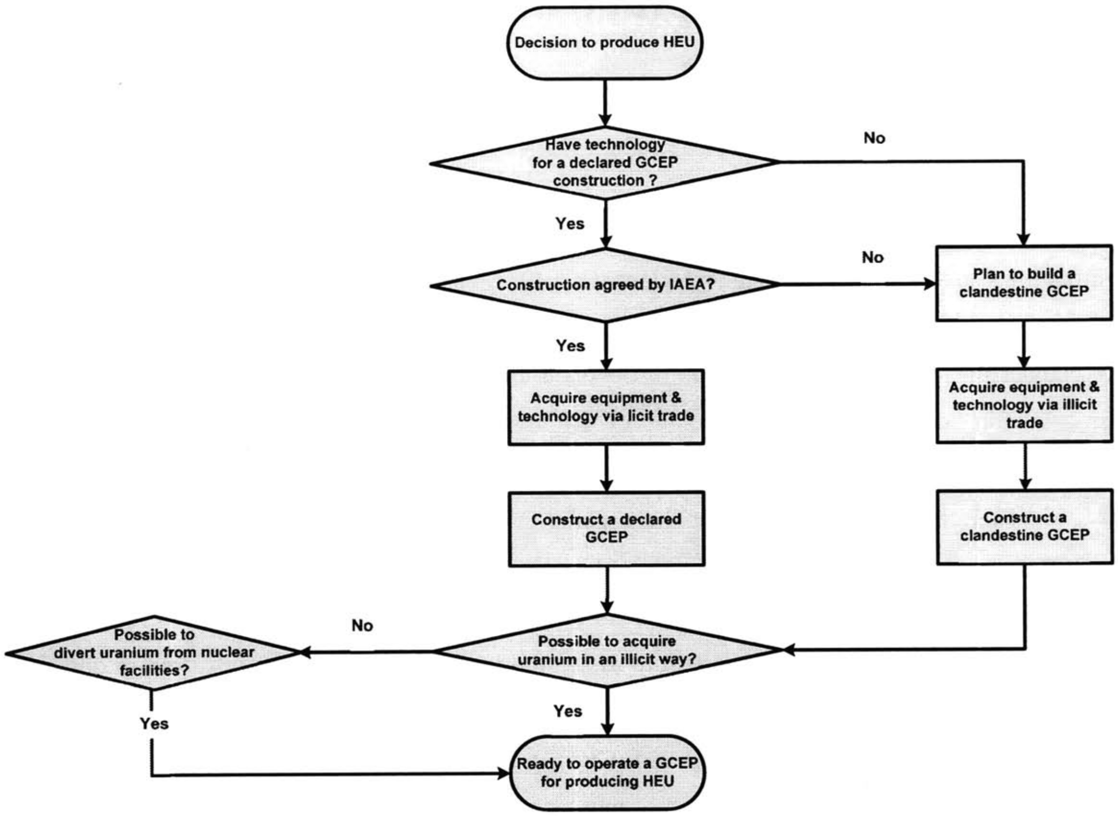

Figure 12.1 Flow Chart of the Process to Prepare for the Production of HEU

Figure 12.1 shows the overall preparation process for the production of HEU. A proliferator may first look at the possibility of constructing a GCEP under IAEA safeguards. If a construction plan is agreed by the IAEA, the proliferator could build a declared GCEP. Otherwise, a proliferator has no choice but to build a GCEP clandestinely. In this case, proliferators must set up a strategy to acquire technology, equipment and nuclear material that can evade safeguards measures of the NPT regime.

12.3 Declared GCEP Construction

12.3.1 A Political Plan for Building a Declared GCEP

In order to construct a declared GCEP, a proliferator should have a plan that includes both legal and technological perspectives. Provided a proliferator possesses either technology or foreign technological assistance, the question may arise whether it would be possible for proliferators to build a declared GCEP. From a legal perspective, three points should be considered when answering this question. First, it remains unclear whether Article IV of the NPT allows the construction of a GCEP. [637] The

[637] This ambiguity adds the ambiguity problem of "*the inalienable right*" in Article IV coupled with "*in conformity with Articles I and II*. Zhang, "The Riddle of Inalienable Right in Article IV of the Treaty on the Non-

international community generally interprets that sensitive nuclear facilities including a GCEP should not be constructed.[638] Second, a state may have bilateral or multilateral agreements signed when receiving nuclear technology from other states for the first time. For example, South Korea is not allowed to enrich uranium or reprocess plutonium without agreement with the United States in advance.[639] Third, in theory, any state subject to only INFCIRC/153-type subsidiary safeguards may build a new nuclear facility and must provide information about the facility to the IAEA 180 days before construction of a new facility can commence.

The proliferator should develop a rationale for claiming the GCEP as an exercise of one's inalienable rights and obtain international support for constructing the facility as part of a nuclear fuel cycle intended for peaceful purposes as described under Article IV of the NPT.[640] Those may include the possession of a large amount of uranium reserve and a reasonably large capacity of nuclear facilities that requires enriched uranium. A potential proliferator may justify his GCEPs as a means of avoiding permanent reliance on foreign-supplied fuel for domestic needs.[641] This is particularly challenging to the NPT regime because the construction of those facilities can be used as a disguise to acquire a potential nuclear weapon capability.[642]

12.3.2 A Technological Plan for Building A Declared GCEP

Once an agreement with the IAEA is reached for a GCEP, the next step is to acquire technology and equipment for constructing and operating the facility. Proliferators should have a technology transfer contract in place with states that have the necessary technology. Those states possessing this technology are presented in Table 12.1. Such a contract is necessary because even though theoretical information and sources with the knowledge to build these facilities have become easily accessible, the construction of GCEPs remains difficult. According to INFCE's report (1980), eight hundred dollars are needed per SWU/yr for GCEP and lead times vary between 1.5 years and 7 years.[643] Table 12.2 lists the requirements to build a GCEP.

Proliferation of the Nuclear Weapons: Intentional Ambiguity.",pp.647-662; and Zarate, "The NPT, IAEA Safeguards and Peaceful Nuclear Energy: An "Inalienable Right," but Precisely to What?."

[638] It is a general notion that even a state with no present intention to acquire nuclear weapons builds a peaceful nuclear industry in anticipation of potential military benefits. In other words, if a situation forces or allows them to acquire peaceful nuclear technology, they can eventually "go-nuclear" much easier.

[639] Agreement for Cooperation between the Government of the United States of America and the Government of the Republic of Korea Concerning Civil Uses of Atomic Energy (Feb.3, 1956). (Revised in 1973)

[640] Japan did not have a problem with constructing its enrichment facilities, whereas Brazil had suffered from the international community.

[641] Iran has built its GCEPs by claiming that it has the right to use nuclear energy for peaceful purposes as prescribed in the NPT; however, they are facing significant opposition from the international community for their highly-likely diversion to military purposes.

[642] For discussion on the establishment of internationally-accepted norm against the proliferation of uranium enrichment technology see Babur Habib et al., "Stemming the Spread of Enrichment Technology," (Woodrow Wilson School of Public and International Affairs, 2006).

[643] IAEA, *Enrichment Availability: Report of INFCE Working Group 2* (Vienna, Austria: IAEA, 1980)., p.10

Table 12.1 Holders of Nuclear Fuel Cycle related Technology or Facilities

Facility type	Holders
U Enrichment Facilities	•Gaseous Diffusion: China, France, and the U.S. •Gas Centrifuge: 12 countries and 17 plants Brazil, China(2), France, Germany, India, Iran, Japan(2), Netherlands, Pakistan, Russia(4), U.K., U.S.
Pu Reprocessing Facilities[644]	France, the United Kingdom, Japan, Russia, and perhaps India, (Pakistan.[645] North Korea)

Table 12.2 Components for GCEP Construction [Albright and Hinderstein (2004)] [646]

Phase		Components
Project design		•Plant construction
Site selection		•Flat land with low seismicity •Good means of transport •Availability of water and electrical power supply
Centrifuge acquisition	**Purchase**	•Turn-key products
	Manufacture	•Centrifuge designs •Manufacturing equipment •Centrifuge manufacturing technology (manual)
Cascade configuration		•Design of optimal cascade configuration •Technical know-how for connecting centrifuges

12.4 Constructing Clandestine GCEPs

12.4.1 A Political Plan for Building a Clandestine GCEP

Proliferators may try to build clandestine facilities due to the challenges of persuading the international community to accept their rationales for having GCEPs. For proliferators, this is a more preferable option than to build a facility under safeguards. There exist two barriers in acquiring technology and equipment in building clandestine GCEPs. First, pre-existing technology holders do not share technology because it is an industrial secret. Second, pre-existing technology holders are subject to MECRs that prohibit the distribution of sensitive technology to states. However, recently, favorable conditions have been created for proliferators concerning the acquisition of technology and equipment because of (a) the technological advancement and diffusion of dual-use technologies and (b) the emergence of nuclear black markets. These factors significantly increased the possibility of acquiring technology and equipment required for building GCEPs.

[644] For more information, see Frans Berkhout, "The International Civilian Reprocessing Business " *Energy and Security*, no. 2 (Jan 1997).
[645] Andrew Koch and Jennifer Topping, "Pakistan's Nuclear-Related Facilities," *The Nonproliferation Review* 4, no. 3 (1997).
[646] Albright and Hinderstein, "Uncovering the Nuclear Black Market: World toward Closing Gaps in the International Nonproliferation Regime".

12.4.2 A Technological Plan for Building a Clandestine GCEP

In the construction of a clandestine GCEP, several factors should be considered carefully. First, the construction of a clandestine GCEP should not be detected by verification resources of the NPT regime. Second, the facility should preferably be protected from possible military air assaults. Third, the facility should be located where the construction can be kept secret to the public even within the state. However, it has become more difficult to build nuclear facilities in secret as the transparency of government policy increases. Zhang (2001) suggests three possible site selection scenarios for constructing clandestine nuclear facilities : [647]

- **Build the facility amid a major industrial site**

  A small GCEP can be built in almost any large industrial building anywhere, including a metropolitan area like a fuel fabrication plant in Canada

- **Build the facility within or near declared sites**

  A small GCEP can be associated with a plant that uses HF or other fluorinated chemicals, thus hiding the potential HF emissions within the background HF already being released. One such example is a manufacturer of fluorinated hydrocarbons

- **Build the nuclear facilities underground**

  Iran's GCEPs at Natanz and Qom, both of which are subterranean.

All of these scenarios may help clandestine facilities avoid possible detection from the NPT regime as well as military strikes by the international community, if any. However, building a clandestine facility in urban areas may involve technological difficulties. Thus, most proliferators try to build facilities far from urban areas. Another challenge associated with clandestine facilities is cost. Moving heavy equipment in adverse weather conditions in order to avoid satellite imagery detection will cost proliferators additional resources and time.[648] Therefore, the overall cost of a clandestine facility is likely to be higher than that of a declared facility.

12.4.3 Other Considerations

Another consideration is the past experience a proliferator has building GCEPs. If a proliferator is already associated with the construction of a declared facility, then this experience can easily be applied

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[647] Zhang, "IAEA-SM-367/16/01".

[648] Israel's reprocessing plant at the "*Dimona nuclear complex*"; the Russian plutonium production facility at "*Krasnoyarsk-26*" (inside a granite mountain on the side of the Yenisey river); and Iranian Gas Centrifuge Uranium Enrichment Plants *at Natanz and at Qom.*

to the construction of a clandestine site.[649] In addition, gas centrifuges in declared GCEPs can be diverted to clandestine ones by claiming that they are broken or destroyed. This option may constitute another proliferation scenario for producing HEU.

The possession of auxiliary or supporting facilities, including gas centrifuge machine manufacturing facilities and Uranium Conversion Facilities (UCF), provides the flexibility to execute any type of proliferation scenario. These facilities significantly save resources for producing HEU clandestinely. In particular, the possession of UCFs allows the proliferation state to convert any form of uranium into UF_6 , a chemical used as feed for GCEPs.

12.5 Elements for Building GCEPs

In order to better understand what is required for the preparation of HEU production at GCEPs, it is necessary to categorize the components that constitute a nuclear program. It is not easy to distinguish the different terminology used in the NPT regime. For this study, these components are classified as (i) nuclear or nuclear-related material, (ii) nuclear or nuclear-related dual-use equipment, and (iii) nuclear or dual-use technology.

While nuclear or nuclear-related material can be clearly defined, the differentiation between equipment and technology is not as clear. Nuclear technology broadly refers to all components required for a nuclear program. In the IAEA, the definition of "nuclear technology" was first developed in 1978.[650] This was a direct result of neither the NPT Article III.2 nor the Zangger Committee list (INFCIRC/209) directly mentioning technology transfer. The Nuclear Suppliers Group (NSG) began to evaluate the need to control intangible technology as a result of its 1999 Plenary Meeting. Only Especially-Designed or Prepared equipment and components (EDPs) of the Zangger Committee (ZC) and Dual-Use Items (DUIs) of the Nuclear Suppliers Group (NSG) are defined as equipment in the present study. Table 12.3 shows the definition for these three elements.

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[649] Albright and Shire, "A Witches' Brew? Evaluating Iran's Uranium-Enrichment Progress," review of Reviewed Item, no.

[650] IAEA, Communication Received from Certain Member States regarding Guidelines for the Export of Nuclear Material, Equipment and Technology, INFCIRC/254/Part.2, (Austria: IAEA, Feb. 1978)

Table 12.3 Definition of Nuclear Elements

Element	Description	Reference
Technology	***Technical data*** in physical form designated by the supplying country as important to the design, construction, operation, or maintenance of enrichment, reprocessing, or heavy water production facilities or major critical components thereof, but excluding data available to the public, for example, in published books and periodicals or that which has been made available internationally without restrictions upon its further dissemination.	IAEA (1978) [a]
	Specific information required for the "development", "production", or "use" of any item contained in the Trigger list. This information may take the form of "***technical data***,"[651] or "***technical assistance***."	IAEA (1992) [b]
Equipment	Devices and components for constructing and operating nuclear facilities. Turn-key products are also included.	NPT Art. III.2
Material	Source material and special fissionable material: nuclear material	NPT Art. III.2
	Nuclear material and radioactive material	IAEA ITDB [c]

Notes
[a] INFCIRC/254 (Feb. 1978)
[b] INFCIRC/254/Rev.1/Part 2 (July 1992)
[c] ITDB stands for Illicit Trafficking Database.

12.6 Transfer of Nuclear Components between States

Given the complexity of nuclear weapons-related technology, potential proliferators will try to obtain foreign assistance to expedite their nuclear weapons programs. This is because foreign assistance is the most common way of obtaining a nuclear program at the initial stage of technology development. Currently, there exist two ways of developing a state's technology through foreign assistance. These are technology transfer and technology acquisition. The distinction between the two methods is based on the degree of participation of those developing and receiving the technology, respectively:

- ***Technology transfer*** – those receiving the technology rely solely on the source of the imported technologies
- ***Technology acquisition*** – those receiving the technology are actively engaged; search for technological solutions; and install, test and commission technologies, working with international suppliers as partners[652]

[651] Institute for Science and International Study (ISIS), E-Book Glossary. < http://www.exportcontrols.org/glossary.html>. Technical data may take forms such as blueprints, plans, diagrams, models, formulae, tables, engineering designs and specifications, manuals and instructions written or recorded on other media or devices such as disk, tape, or read-only memories. Technical assistance by foreign experts is important to every step of developing a nuclear weapons program. It can not only make the programs successful, but can also shorten the time required to complete the programs. Even if would-be proliferators were to acquire facilities and material, it would not be easy to operate or to divert facilities into military purposes without a significant amount of experience accumulated for a long time.

Koblentz (2005) reviewed the question of why and how states and non-state parties share nuclear weapons technology. He suggests a variety of ways for proliferators to obtain nuclear technology from others as summarized in Table 12.4.[653] According to his definition, nuclear sharing or cooperation and provision fall into the category of nuclear transfer.

Table 12.4 Various Ways for Nuclear Technology Diffusion [Koblentz (2005)]

Paths		Description	Cases
1	**Nuclear Sharing or cooperation**	The knowing and willful transfer of nuclear weapons-related technology to a non-nuclear actor	United States to United Kingdom (1943-1946) Pakistan to Libya (1997-2003) [a]
2	**Provision**	The provision of civilian nuclear technology for peaceful purposes	Canada's supply of the CIRUS research reactor to India in the 1960s
3	**Sales**	Sales of nuclear technology by private entities without the knowledge of their host government	German firms and individuals to the Iraqi program in the 1980s
4	**Theft**	The theft of nuclear technology by a state	The Soviet Union's espionage during the 1940s
5	**Nuclear trafficking**	The illicit procurement and smuggling of nuclear technology	Pakistan's A. Q. Khan network since the 1970s[654]
6	**High-Tech Bartering** [b]	Exchange for complementary technology acquisition	North Korea and Pakistan Israel and South Africa

Notes
[a] Koblentz suggests a total of eleven cases of nuclear cooperation.
[b] Complementary cooperation

Historically, almost all countries have acquired nuclear technology with foreign assistance in the form of transfer or trade,[655] although many states claim otherwise.[656] Whatever the purpose of nuclear

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652 Marcelle, *Policy Briefs, Technology Acquisition and Domestic Learning*. He also explains two models for acquiring technology: a linear model and a nonlinear model. For more discussion on the acquisition of new technologies, see Annette L. Ranft and Michael D. Lord, "Acquiring New Technologies and Capabilities: A Grounded Model of Acquisition Implementation," *Organizational Science* 13, no. 4 (Jul.-Aug. 2002)., pp.420-441.

653 Gregory D. Koblentz, "The Politics of Nuclear Cooperation: Why States Share Nuclear Weapons Technology?" (paper presented at the 2005 Annual Meeting of the American Political Science Association, Sep. 1-4 2005).

654 Albright and Hinderstein, "Uncovering the Nuclear Black Market: World toward Closing Gaps in the International Nonproliferation Regime".

655 The author distinguishes transfer from trade in that trade is the activity of exchanges items in anticipation of rewards. Otherwise, transfer does not necessarily require the exchange such as assistance or cooperation.

656 Thomas C. Reed and Danny B. Stillman, *The Nuclear Express : A Political History of the Bomb and Its Proliferation* (Minneapolis: Zenith Press, 2009).

technology transfer, it can save proliferators many years and millions of dollars.[657] For this reason, all recent proliferators developed their nuclear weapons programs in cooperation with other states or via the black market. The transfer of nuclear elements would allow states with minimal nuclear infrastructure to become nuclear-armed states.

The cases of Iran and Libya demonstrate the effectiveness of developing nuclear weapons technology with foreign assistance. Iran failed to develop a nuclear weapons program after several decades of trying, but was able to establish a uranium enrichment program within a decade after illicitly purchasing gas centrifuge enrichment technology from Pakistan. Libya successfully assembled a laboratory-scale uranium enrichment plant through the nuclear black market network in five years. This success followed twenty years of failed attempts to do so on their own. Before their program was revealed, Libya had purchased 10,000 maraging steel centrifuges, sufficient to produce as many as ten bombs in a year in the form of turn-key products.

12.7 Trade of Nuclear Elements

12.7.1 Definition of Illicitness for International Trade

In order to establish an approach to analyze how proliferators access nuclear elements and how safeguarders could control this access, possible ways of trading nuclear elements should be discussed from a legal perspective. Criteria to determine the legality of nuclear trade may include UNSC resolutions, the NPT, IAEA safeguards, and domestic legislation of the concerned parties.[658] There exist legal disputes about the definition of "licit or lawful trade" among international law scholars, usually the point at which international treaties become legally effective. Andrew Prosser (2004)[659] defines the concept of illicit nuclear trafficking as follows:

> *(i) the diversion, purchase, sale or transfer of nuclear or radioactive material or nuclear weapons-usable equipment in violation of local, national, or international law, including UNSC 1540 (2004) and the NPT and*
> *(ii) trafficking incidents where there is reason to believe that trafficked items could be destined for weapons end-use, even where such trafficking does not violate any law.*

In the present study, Prosser's (2004) definition is used to define the illicitness of nuclear elements acquisition. Various terms are used to describe illicit trade activities as shown in Table 12.5. Only

[657] Koblentz, "The Politics of Nuclear Cooperation: Why States Share Nuclear Weapons Technology?"
[658] It is noteworthy that the NPT and UNSC resolutions based on United Nations Charter Chapter VII were empowered to have legal authorities as international treaties. In general, international treaties will not legally effective until signatories reflect provisions of treaties into their legislative system. Hanson, *Legal Method & Reasoning.*
[659] Andrew Prosser, *Nuclear Trafficking Routes: Dangerous Trends in Southern Asia* (Center for Defense Information, Nov. 22 2004 Feb. 1]); available from http://www.cdi.org/PDFs/TraffickingSmuggling.pdf.

Prosser (2004) and the International Institute for Strategic Studies (IISS) (2008) distinguish illicit trade for different components: material, equipment, and technology.

Table 12.5 Definitions of Terminology for Illicit Trade

Reference	Equipment and technology	Material
IAEA ITDB (1995) [660]	-	Illicit trafficking
CNS	-	Nuclear trafficking
IAEA (2007) [661]	-	Nuclear smuggling
CISAC [662]	-	Nuclear smuggling
Prosser (2004)	Illicit nuclear trafficking in equipment and technology	Illicit nuclear trafficking in nuclear material (nuclear smuggling) [b]
IISS [2008]	Illicit trade	Nuclear trafficking

Notes
[a] James Martin Center for Nonproliferation at the Monterey Institute of International Studies (CNS) and Center for International Security and Cooperation, Stanford University (CISAC)
[b] The term "nuclear smuggling" is confined to the description of the trafficking of material (either nuclear or radioactive).

Unlike Prosser, the IISS uses 'nuclear trafficking' to refer to activities involving materials and 'illicit trade' to describe activities involving nuclear technology and equipment, when discussing nuclear black market activity.[663]

12.7.2 Classification of Nuclear Trade

Ways to purchase or acquire nuclear elements can be classified into the following three cases: (a) licit interstate trade, (b) illicit interstate trade, and (c) illicit trade via nuclear black markets.

Case #1: Licit Interstate Trade

The definition of ***licit trade*** between states tends to vary. Generally, in any international market, trade is considered licit as long as interstate trade does not violate domestic legislation of both parties or any international treaties. When referring to the trade of nuclear elements in the NPT regime, trade can be defined as licit as long as it is conducted under IAEA safeguards. Therefore, NPT non-member states

[660] IAEA, "ITDB Fact Sheet: IAEA Information System on Illicit Trafficking and Other Unauthorized Activities Involving Nuclear and Radioactive Materials," (IAEA, 2007). Established in 1995, the ITDB is the IAEA's information system on incidents of illicit trafficking and other unauthorized activities and events involving nuclear and radioactive materials.
[661] IAEA, "Combating Illicit Trafficking in Nuclear and Other Radioactive Material," in *Nuclear Security Series No.6* (2007).
[662] Database on Nuclear Smuggling, Theft, and Orphan Radiation Sources (DSTO) But, access is restricted.
[663] John Chipman, *Press Statement on IISS Strategic Dossier, "Nuclear Black Markets: Pakistan, A.Q. Khan and the Rise of Proliferation Networks - a Net Assessment"* (2007 [cited Dec. 11 2008]); available from http://www.iiss.org/publications/strategicdossiers/nbm/nuclear-black-market-dossier-press-statement/.

can export their nuclear elements to proliferators without applying for Article III of the NPT. Furthermore, trade activities involving NPT non-members are not defined as illicit activities according to the norm of international law since non-member states are actually in violation of neither an international treaty nor a domestic law.

Case #2: Illicit Interstate Trade

If NPT member states are involved in any trade with no safeguards applications such as nuclear technology bartering, it can be defined as illicit interstate nuclear trade.[664] Even member states that have good reputations are occasionally tempted to export sensitive items to other states for economic or political profit.

Case #3: Illicit Trade via Nuclear Black Markets

A "black market" refers to a market in which certain goods or services are routinely traded in a manner contrary to the laws or regulations of the government in power. The IISS defines nuclear black market as "the trade in nuclear-related expertise, technologies, components or material that is being pursued for non-peaceful purposes and most often by covert or secretive means." The NPT regime should pay the closest attention to nuclear black market networks because they are very hard to detect and operate very efficiently. The emergence of a multinational illicit network, so-called *A. Q. Khan network*, has seriously threatened the current nonproliferation regime.

Illicit trade via nuclear black markets can take place between a state and small groups or even individuals. Once an illicit procurement channel is established, it enables the proliferators to penetrate even embargos.[665] In general, it is difficult to define illicit interstate trade as explicitly 'illegal' if the proliferators thoroughly exploit loopholes in Multilateral Export Control Regimes (MECRs) and national export control systems either at government or company levels.

12.8 Tactics for Acquiring Undeclared Uranium Feed

12.8.1. Material Flow

Uranium exists in various physical/chemical forms and in a range of enrichment ratios. A proliferator will decide what chemical forms and in what quantity uranium needs to be purchased. For example, the illicit purchase of Non-UF6 [i.e., Uranium Ore Concentrate (UOC)], a form of NU, is much easier than NUF6, LEU, and HEU to acquire for several reasons. First, the number of countries that can export UOC is much higher than those that can export NUF6, LEU or HEU because countries that have

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[664] For more information see the website, Institute for Science and International Security (ISIS), *Illicit Nuclear Trade Projects and Chronological Isis Reports on Illicit Nuclear Trade* ([cited Nov. 11 2008]); available from http://www.isis-online.org/publications/expcontrol/.

[665] Institute for Science and International Security (ISIS), *Iraq's Acquisition of Gas Centrifuge Technology Part II: Recruitment of Karl Heinz Schaab*.

uranium enrichment and conversion capability are few, approximately twelve. Second, safeguards for LEU- or HEU- containing facilities are stricter than those for uranium mining and milling facilities that produce NU. If a proliferator does not have UCFs within the state, he should be able to acquire undeclared uranium in the form of UF_6. Otherwise, he cannot operate GCEPs.

Figure 12.2 shows a variety of ways to acquire uranium feed for producing HEU. The following conclusions can be drawn from the figure:

- Existence of a black market and possession of uranium conversion facilities increases the degrees of freedom in the acquisition of uranium material.
- It is obvious that the more complete a nuclear fuel cycle a proliferator has, the higher the probability a proliferator can acquire weapons-usable material. In particular, the possession of Uranium Conversion Facilities (UCFs) increases the degree of freedom in obtaining HEU for proliferators.

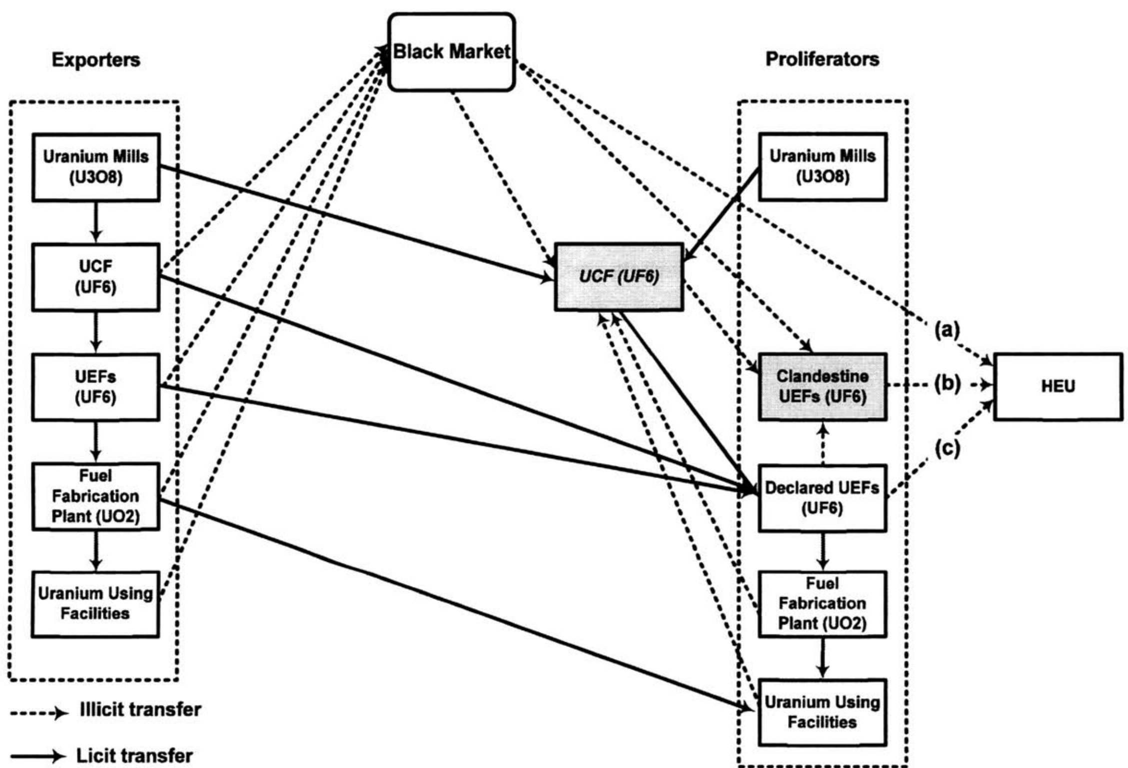

Figure 12.2 Schematic of Possible Nuclear Material Flow

The right side of Figure 12.2 shows three possible ways to acquire HEU for nuclear weapons: (a) direct purchase of HEU, (b) production of HEU from clandestine GCEPs, and (c) production of HEU from declared GCEPs. Pathway (a) is feasible, but unlikely for two reasons. First, states require continued recognized as de-facto nuclear weapon states. Second, it is very difficult to obtain Significant

Quantities (SQs) of HEU through black markets. In other words, the possession of a few nuclear weapons does not guarantee an effective exploitation of nuclear weapons tactics or strategy, such as a second-strike capability. Thus only (b) and (c) are considered plausible options for HEU acquisition.

12.8.2 Illicit Acquisition of Material

There are generally three ways to acquire uranium in an illicit way: nuclear smuggling via nuclear black markets, interstate trade or cooperation, and uranium mine development within the territory of nuclear proliferation without an IAEA safeguard application. These scenarios are shown in Figure 12.3. However, there are some situations where the illicitness of nuclear material-related activities cannot be clearly defined.

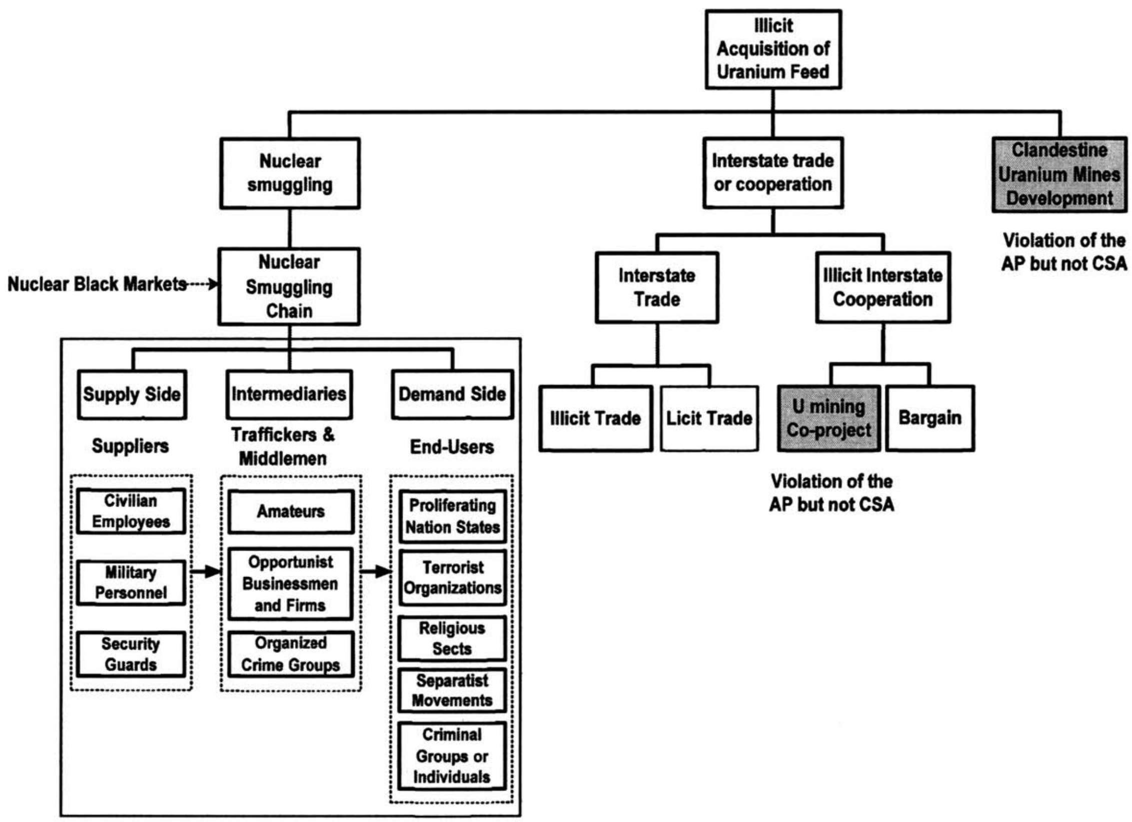

Figure 12.3 Possible Nuclear Material Acquisition Paths[666]

Table 12.6 shows a case study of how Iran obtained nuclear materials for the operation of its nuclear facilities.

[666] Nuclear smuggling chain is obtained from Lyudmila Zaitseva and Kevin Hand, "Nuclear Smuggling Chains: Suppliers, Intermediaries, and End-Users," *American Behavioral Scientist* 46, no. 6 (Feb. 2003)., pp.822-844. U mining co-project means cooperation with countries that have uranium resources. And bargain means a proliferator can get uranium material in return for other technologies or weapons. Please see Appendix for cases.

Table12.6 Nuclear Material Acquisition Paths Focused on Iran's Case

Path		Cases
Interstate trade or cooperation	**Interstate contract**	•In the 1970s, Iran purchased yellowcake from South Africa. •In 1991, China and Iran announced China's agreement to supply Iran's first nuclear reactor, a 20 MW research reactor.[667] China is also widely acknowledged to have provided Iran with 400 kg of uranium dioxide. •In 1992, Russia and Iran made the inter-governmental agreements for the Busher Reactor, which assured the supply of prefabricated fuels. •In 2009, Venezuela, and Bolivia are supplying Iran with uranium.[668]
	Bargain	•In 2006, Iran tried to obtain uranium from Somalia in return for supplying weapons to the anarchic country's Islamist movement.[669]
	Uranium co-mining project	•In 2002, Iran launched a uranium-mining project in Azerbaijan.[670]
Smuggling		•In 2005, Iran tried to smuggle some U-238 by ship from Congo to Bandar Abbas.[671]
Uranium mine development		•Since 1988, Iran reportedly opened as many as 10 uranium mines, including the Saghand uranium mine in Yazd province.

A. Nuclear Smuggling

It is important to understand that there is a high probability that some categories of nuclear material can be potentially traded in nuclear black markets as reviewed in chapter 6. It is estimated that there is more than 1,000 tons of reactor plutonium in spent fuel worldwide and 2,000 tons of HEU in weapon stockpiles, civilian reactors, and military reactors on ships and submarines.[672] A state that lacks control of nuclear material and activities, the former Soviets Union for example, may risk becoming the target of non-State actors that are involved in the proliferation of nuclear weapons technology or in clandestine nuclear-related activities.

Sources of nuclear materials traded illicitly can be smuggled from nuclear facilities by government officials and workers. Table 12.7 shows some nuclear material trafficking incidents that have occurred since the end of the Cold War. The type and quantity of illicitly-traded materials vary significantly.

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[667] Nuclear Threat Initiative (NTI), *China's Nuclear Exports and Assistance to Iran* (Sep. 23 2003 [cited Aug. 28 2009]); available from http://www.nti.org/db/china/niranpos.htm.
[668] Mark Lavie, *Secret Israel Report: Venezuela, Bolivia Supplying Iran with Uranium for Its Nuclear Program* (The Huffington Post, May 25 2009 [cited June 25 2009]); available from http://www.huffingtonpost.com/2009/05/25/secret-israeli-report-ven_n_207405.html.
[669] Jihad Watch, *Iran Tried to Get Uranium by Arming Somalia* (Jihad Watch, Nov.16 2006 [cited Jan. 5 2009]); available from http://www.jihadwatch.org/archives/014070.php.
[670] Nuclear Threat Initiative (NTI), *Research Library: Iran Mining Uranium in Azerbaijan, Baku Newspaper Reports* (2002 [cited Feb. 5 2009]); available from http://www.nti.org/db/nistraff/2002/20020210.htm.
[671] But this was foiled by Tanzanian customs officials.
[672] Garwin and Vadim, "Nuclear Weapon Development without Nuclear Testing?"

Table 12.7 Cases of Nuclear Smuggling [Zaitseva and Hand (2003)]

Time	Supplier		End-User	Intercepted place	Type	Quantity
1992	Russia	Military officers	North Korea	Not intercepted	Pu	N/A
1993	Russia	Trading firms	North Korea	Lithuania	Be	4.4 tons
					50% HEU	100 gram
1993	N/A	A group of smugglers and Iranian Secret Service Agents	Iran	Turkey	NU	2.5 kg
1994	N/A	Adolf Jaekle	Iraq	Germany	WGPu	6.2 g
2000	N/A	Three individuals	Iran	Kazakhstan	LEU fuel pellets	4 kg

B. Interstate Trade of Material

Several pathways may be identified where proliferators can acquire nuclear material through long-term weaknesses in IAEA safeguards. In particular, the international transfer of nuclear material before the starting point of safeguarding is highly subject to remain undeclared to the IAEA. Many UOC-producers or potential producers, such as African countries, do not have effective national control of uranium production and export.[673] Possible weaknesses of the IAEA are identified in Tables 12.8 and 12.9 and show the current status of safeguard application for four different types of uranium materials considered in the study.

Table 12.8 Safeguards Application for Uranium Material for Domestic Use

Category	Concentration Plant (U3O8)	Conversion Plant (UF6) [674]	Enrichment Plant (UF6) [c]	Fuel fabrication Plant (UO2)
UOC (yellow cake) [a]	•Not subject to CSA [Para 34 (a), (b)] [b] •Subject to AP			
NUF6	subject to CSA [34 (c), CSA]			
LEUF6	subject to CSA [34 (c), CSA]			
LEU	subject to CSA [34 (c), CSA]			

Notes
[a] UOC (Uranium Concentrated Oxide), which is produced by refining uranium ore from uranium mines
[b] If the material is present in quantities exceeding 10 MTU. The provision of this information does not require detailed NMA [Article 2 (vi)(a)].
[c] Only for Gas Centrifuge Enrichment Plants (GCEP) and Gaseous Diffusion Plants (GDPs)

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[673] The IAEA and various governments are conducing outreach/capacity building for NU producers to help establish effective national control of uranium production and export.

[674] According to IAEA Policy 18 (2003)The starting point of safeguards was changed from the output of the conversion plant to no later than the first point in the conversion process at which the material meeting paragraph 34 (c) of CSA leaves the process state in which it is produced. Any purified aqueous uranium solution or any purified uranium oxide to be considered to be declared. However, the application of safeguards procedures may not be practical or economical. In such cases, therefore, the procedures should be applied at the first practicable point earlier (i.e., "upstream") in the plant. In some of these cases, the first practicable point might be the UOC input at the beginning of conversion process. For more information, see Owen, "Implementation of IAEA Policy Paper 18 in Canada, IAEA-CN-148/39".

Table 12.9 Safeguards Application for Nuclear Material for Trade

Case	Description	Reference
No control over international transfer of UOC [a]	•Under the CSA, a uranium supplier does not need to notify the IAEA of any source material containing uranium or thorium which has not yet reached the composition and purity suitable for fuel fabrication or for being isotopically enriched, if it is ***for non-nuclear use***[b]	CSA [Para. 34 (b)]
	•The AP requires information regarding the international transfer of source material in quantities exceeding ***10 metric*** **tons** of uranium though it is for non-nuclear use.[c]	AP [Art. 2.(a)(vi)]
Non-application of early notification requirement	Under CSA, a state should provide ***early notification*** of material transfers to the IAEA in two cases. [d] (1) Nuclear material in an amount exceeding one effective kilogram or (2) Successive shipments to the same state within a period of three months each of less than one effective kg but exceeding in total one effective kg.[675]	CSA [Paragraphs 91-96]

Notes
[a] Uranium Ore Concentrate (UOC) is nuclear materials before the starting point of safeguards
[b] AP Art. 2 a. (vi)(b) requests a state to report source material for non-nuclear purposes in quantities exceeding 10 metric tons of uranium and 20 metric tons of thorium even if it is for specifically non-nuclear purposes.
[c] Information shall be provided to the IAEA, upon the request by the IAEA.
[d] Otherwise, notification of international transfer would be made annually.

Though the IAEA recognizes these weaknesses, there are currently no inspection procedures for detecting the international transfer of Uranium Ore Concentrates (UOC). This is because it is highly likely that this material remains unprocessed which does not induce safeguards concern, though there is a possibility that a proliferator can process undeclared UOC. Currently, the detection of UOC transfers by the IAEA solely depends on reports provided by suppliers and receivers, analysis of open source information, and provision of national intelligence information. However, under the AP, the IAEA can carry out complementary access to UOC-producing facilities.[676]

C. Uranium Mine Development within the Proliferation State

Article 2. a (v) of the Additional Protocol (AP) requests states to report operational status and the estimated annual production capacity of uranium mines. Therefore, uranium mine development without reporting to the IAEA is in violation of the AP. However, countries not governed under the AP can develop their uranium mines without violating safeguards. Iran and North Korea are good examples. In

[675] An effective kilogram is a special unit used in the safeguarding of nuclear material as defined in paragraphs 104 of INFCIRC/153 and para.72 of INFCIRC/66. In addition, according to Chapter 7 of the Euratom Treaty, notification is not required if the quantity does not exceed one effective kilogram during transfers of material between states.
[676] Personal communication with John Carlson, Nov.22, 2009 via e-mail.

particular, North Korea is estimated to have a significant amount of uranium reserves. Thus, if North Korea were to develop these reserves in full scale, it could pose a significant threat on the NPT regime.

12.9. Diversion of Uranium Feeds

Uranium can be provided to GCEPs through diversion from declared nuclear facilities. Figure 12.4 shows the overall schematic of how uranium can be diverted from a typical nuclear fuel cycle A. From the figure, a path of uranium acquisition can be identified. For example, $LEUF_6$ can be made in four ways: (a) diverting $LEUF_6$ product from a declared GCEP, (b) converting diverted LEU from nuclear reactor facilities or LEU Fuel Fabrication Plants (FFPs), (c) converting illicitly acquired LEU, and (d) acquiring $LEUF_6$ directly through illicit trade.

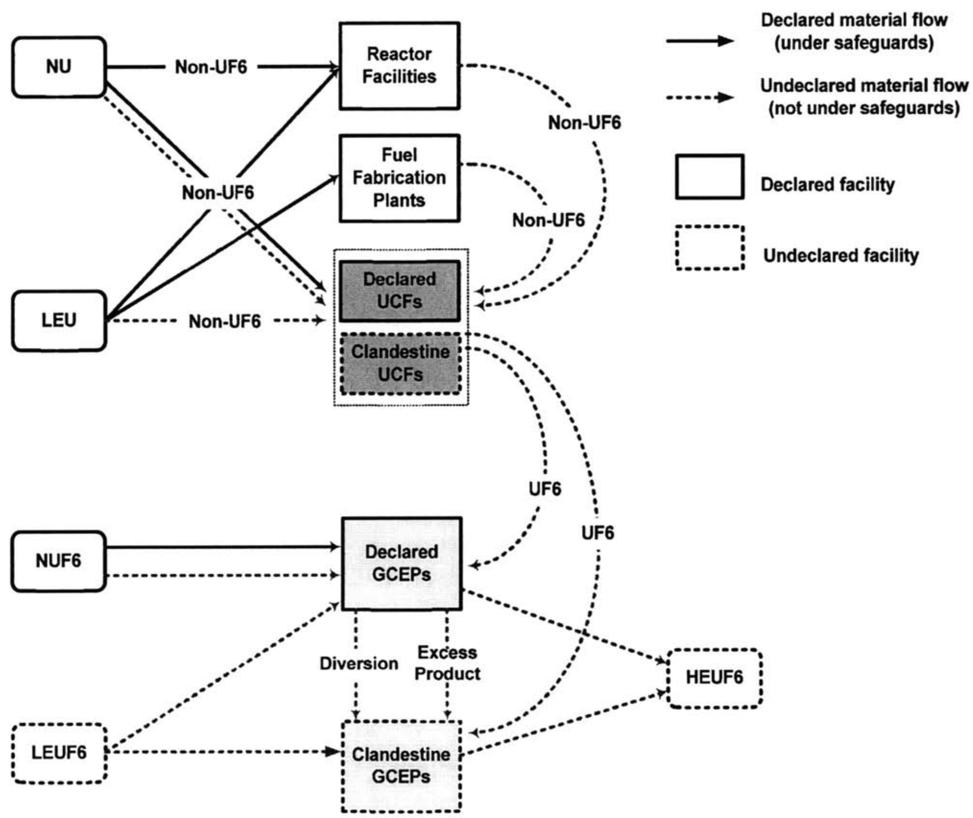


Figure 12.4 Uranium Flow toward HEUF6 Production

Table 12.10 gives a brief description of nuclear facilities referenced in the present study. Referenced UCF or GCEP facilities were selected based on available literature in order to take advantage of study results.

Table 12.10 Description of Referenced Facilities

Facility type	Capacity for the Study	Reference
Fuel fabrication plants (FFPs)	**The nominal capacity of 500 [MTU/yr] [a]**	Areva[677]
Nuclear reactors facilities	**The total capacity of 1000 [MWe]** (in consideration of Iran's Busher Reactor capacity)	Typical reactors
Uranium conversion facilities (UCFs)	**100 MT of Yellow Cake/yr [b]**	Elayat et al. (2004)[678]
GCEPs	**500,000 kgSWU/yr**	LISSAT modeling

Notes
[a] 400MTU/yr is the capacity of South Korean LWR Fuel Fabrication Plant. And 650MTU/yr is the capacity of Advanced Nuclear Fuels (ANF) Lingen, Germany
[b] Lingen has a capacity of 500 MTU/yr.

12.9.1 Diversion of Nuclear Material from Nuclear Reactor Facilities, FFPs, and UCFs

Nuclear material can be diverted from any type of nuclear facility, including rector facilities, FFPs, and UCFs, located within a proliferation state [See Appendix H]. A proliferator can divert uranium materials from declared nuclear facilities in three ways: diversion by biasing (data manipulation or falsification), diversion in material unaccounted for (MUF), and diversion using dummies. At UCFs, UF_6 can be diverted easily at the cold traps, where the effluent stream of UF_6 is cooled to -10°C and condensed from the hot effluent gases as it passes through.[679] At FFPs, either UF6 or fuels in UO2 can be diverted in the same way mentioned above.

12.9.2 Diversion of UF6 from GCEPs

As mentioned previously, there are three ways to divert UF_6 at declared GCEPs. These include (a) excess production of LEUF6 with undeclared supplies, (b) diversion of already produced LEUF6, and (c) diversion of NUF6 feed.

A. Excess Production of $LEUF_6$ Using an Undeclared Uranium Supply

Excess $LEUF_6$ can be produced without detection if proliferators can operate in off-design modes, coupled with some manipulation of the operating record. The following methods can be implemented:

- **Increasing operation time**

[677] http://www.areva-np.com/common/liblocal/docs/Brochure/Fuelsect_eng_def.pdf
[678] H.A. Elayat et al., "Systems Analysis of Safeguards Effectiveness in a Uranium Conversion Facility". The analysis was done mainly through evaluating MUF indicators with regard to the diversion of UF6 from a cold trap.
[679] Nuclear Threat Initiative (NTI), *Uranium Feedstock* ([cited Feb. 11 2009]); available from http://www.globalsecurity.org/wmd/intro/u-feedstock.htm.

Proliferators can operate a GCEP for a longer time than declared, claiming the additional time for maintenance activities.

- **Incorporating modularized cascades**

  Proliferators can modularize undeclared gas centrifuge cascades within a declared facility. Doing so would provide an additional capacity of centrifuges and allow centrifuge operation to continue during non-inspection periods. The additional SWU capacity can be added by replacing existing centrifuge machines with an advanced design of cascades.[680]

- **Increasing production rate**

  Proliferators can operate the facility at an increased production rate at the expense of efficiency. Excessively produced $LEUF_6$ can be diverted and stockpiled for later purposes such as production of HEU at clandestine GCEPs.

B. Diversion of $LEUF_6$ Product from GCEPs

Normally-produced $LEUF_6$ at declared GCEPs can be diverted if proliferators can utilize the uncertainties of Nuclear Material Accountancy (NMA) or employ fake tactics as follows:

• Diversion by biasing (Data manipulation)

HEU can be diverted either through undeclared operations at a declared facility or by modifying the quantity of material in declared inventories. Diversion by data manipulation at uranium enrichment facilities includes (i) overstating or understating weight values of shipped/received UF6 cylinders recorded by the Load Cell Based Weighing System (LCBS); (ii) overstating or understating the purity of UF_6; (iii) overstating/understating isotopic assay of uranium (enrichment level); and (iv) removing undeclared cylinders following an inspection announcement and prior to the subsequent access of IAEA personnel to the UF_6 feed and withdrawal area.

• Diversion in Material Unaccounted For (MUF)

MUF is a quality indicator of the control of nuclear materials, which is obtained by simply subtracting "Book Inventory" from "Physical Inventory." The International Target Values (ITVs) provide standard uncertainties for measurement of nuclear materials and thereby establishing reasonable values of MUF.[681] At GCEPs, a proliferator could divert LEU from the declared UEFs or other facilities under the guise of material-unaccounted-for (MUF) by taking small amounts of material over a long period of

[680] E.A. Hakkila et al., *The Safeguards Options Study*. p.96.

[681] H. Aigner et al., "International Target Values 2000 for Measurement Uncertainties in Safeguarding Nuclear Materials," *ESARDA Bulletin* 31 (2008). The ITVs reflect the current state of measurement capabilities attainable for DA and NDA techniques in performing safeguards verification activities. The published ITVs are designed to provide a reference of the quality of measurements in nuclear material accountancy.

time (diversion by skimming). Skimming scenarios at GCEPs were reviewed using LISSAT. Possible scenarios are summarized in Table 12.11.

Table 12.11 Possible Skimming Scenarios at GCEPs using LISSAT

Specification	Elayat et al. (2006) [682]	Lambert et al. (2007)[683]
Capacity	500,000 kgSWU per year [a]	
Cascade composition	50 cascades of 250 centrifuges each	
Product uranium enrichment ratio	3.5%	
MUF	2% of the product	
Diverted amount of U-235 using MUF	2000 kg of LEU, containing 70kg of U-235	2300 kg of LEU, containing 80 kg of U-235.

Note: [a] This is the capacity that can produce 115,000 kgU/yr in the form of UF_6 enriched to 3.5% (MUF for the product is around 1,000 kg).

•Use of Dummy Cylinders

A proliferator could replace feed cylinders with inactive dummies or with dummies which mimic the material taken (such as borrowing equivalent material from another facility within the State).

C. Diversion of NUF6 Feed at GCEPs

NUF6 can be diverted at GCEPs in two ways. First, the nuclear material values can be falsified for a larger number of cylinders. Credibly falsifying the enrichment or purity of NUF6 is not an easy task. However, this problem can be circumvented by falsifying the gross-empty weights of cylinders returned to the NU conversion facility, particularly if the facility is owned by the proliferator. For this to be considered a profitable option, nearly every cylinder would have to be falsified to get 1 SQ. However, the practice of falsifying cylinders has a fairly high probability of detection by the IAEA. A second option is to divert the entire contents of feed cylinders (two NUF6 cylinders for 1 SQ). This is a more successful option than the former since there is an increased likelihood that the IAEA will not select one of two entirely-diverted cylinders. Considering that the IAEA's goal for detection of 1 SQ of diverted NU is set to 50 percent, this particular strategy may be considered self-explanatory.

12.10 Conversion of Undeclared Uranium at Declared UCFs

The possession of UCFs significantly increases the flexibility of a proliferator's control over uranium processing. The reason being, UCFs can convert uranium to any ratio of uranium enrichment. Any

[682] For more information see H.A. Elayat, W.J. O'Conell, and B.D. Boyer, "Gas Centrifuge Enrichment Plant Safeguards System Modeling" (paper presented at the 47th Annual Meeting for the INMM, Nashville, TN, July 16-20 2006).
[683] H. Lambert et al., "LISSAT Analysis of a Generic Centrifuge Enrichment Plant" (paper presented at the Proceedings of the 48th Annual Conference of the INMM, Tucson, AZ, 2007).

material diverted from FFPs or nuclear reactor facilities must be processed at UCFs before being introduced into GCEPs or nuclear warhead manufacturing. Without UCFs, undeclared, diverted non-UF6 nuclear material must be processed in foreign territories. This restriction to process increases the possibility of detecting proliferation activities. To avoid detection and for the reasons mentioned above, UCFs require serious control from a safeguarders' point of view.

However, the question may arise as to whether or not LEU can be processed at a UCF designed for the conversion of NU. The answer is yes. In order to do so, uranium concentrations would require careful controlling during some steps of processing. Typically, the equipment in NU conversion facilities is very large, depending on the throughput, since there are no restrictions on equipment size from a fission criticality point of view. However, aqueous LEU in dissolution and solvent extraction processes are highly subject to restrictions due to fission criticality concerns.[684] Thus, some of the aqueous processing vessels (dissolvers, solvent-extraction pulse columns, or solvent-extraction mixer-settlers) at NU conversion plants may not be safe for processing LEU. However, the accidental formation of a critical mass of LEU in equipment handling dry materials is extremely remote. Therefore, the conversions of UO2 to UF4 and UF4 to UF6 would not present a problem for processing Non-UF6 form of LEU in equipment sized for NU.

The additional conversion operation at declared UCFs follows a procedure similar to the excess production of LEU at GCEPs as follows: (a) operate the facility for an additional time than originally declared; (b) increase the product rate to higher than normal operation; and (c) use add-on capacity within the facility.

12.11 Conclusion

A possible strategy for establishing a uranium enrichment program using a GCEP was reviewed in terms of the construction of GCEPs and the preparation of uranium material through illicit acquisition and/or diversion. These results will be used for the development of an integrated model in Chapter 14 of this thesis. The importance of controlling the transfer or trade of nuclear elements required for uranium enrichment was discussed. It would be more effective for the NPT regime to control the movement of nuclear material rather than merely attempt to detect a clandestine GCEP after it has been constructed. The latter option is very limiting from both a technical and political perspective.

[684] Finis S. Patton, John M. Googin, and William L. Griffith, *Enriched Uranium Processing* (New York, NY: Pegamon Press, 1963).. On page 156, Table 7 shows that for NU, the maximum safe cylinder diameter (relevant to solvent-extraction pulse columns) and the maximum safe slab thickness (relevant to mixer-settler equipment) are infinite. However, for 5% U-235, the maximum numbers are 10 inches and 5 inches, respectively.

CHAPTER 13 A PROLIFERATOR'S STRATEGY FOR HEU PRODUCTION: PART II

13.1 Introduction

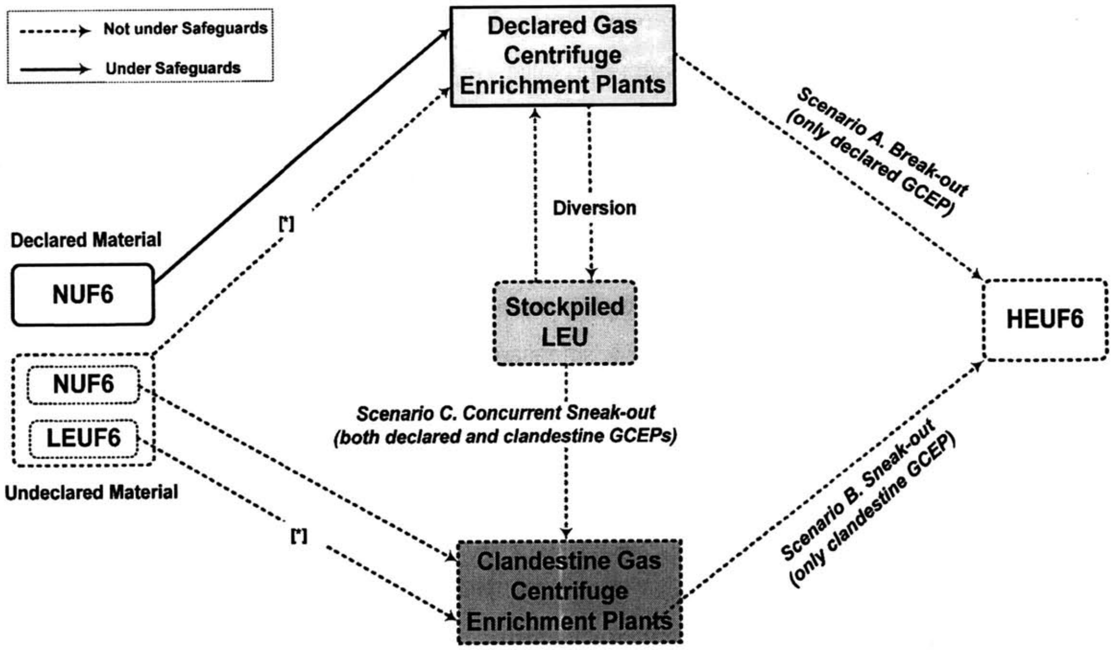
This chapter develops several possible scenarios in which proliferators can produce HEU given that GCEP, either declared or clandestine, and uranium material for feed are available as discussed in Chapter 12. Once proliferators decide to produce HEU a coherent plan needs to be developed on how to successfully accomplish their illicit activities. Furthermore, the plan should include measures that can minimize costs in association with the international community's response.

There have been some good studies on possible proliferation scenarios for producing HEU using GCEPs. However, those studies were limited to taking into consideration only a technical perspective. Proliferation scenarios should be understood from both political and technical perspectives. Developing scenarios that integrate these two perspectives is critical to both identifying weaknesses of the current NPT regime and establishing effective strategies to deal with proliferation scenarios.

In general, proliferation scenarios for producing HEU are classified into three cases: (i) break-out scenario at declared GCEPs, (ii) sneak-out scenario at clandestine GCEPs, and (iii) the concurrent sneak-out scenario at both declared and clandestine GCEPs. Considering historic precedence, the focus of analysis in this chapter is given to the break-out scenario. From a political perspective, a timeline for executing the break-out scenario is developed and divided into aggressive and defensive scenarios. From a technological perspective, a technical description about some ways to divert a declared LEU-producing GCEP into a HEU-producing GCEP is analyzed. Finally, this chapter concludes by comparing different sub-scenarios under the break-out scenario. The results provide insight into the possible improvement of IAEA safeguards at GCEPs.

13.2 HEU Production Scenarios

Three scenarios for producing HEU by proliferators can be envisioned based on two types of GCEPs, a clandestine and a declared GCEP. First, a country with an enrichment facility that can produce LEU in substantial quantities can modify such a facility to produce HEU, but such modifications increase the risk of detection. Second, a country may produce HEU using a clandestine, dedicated GCEP only. Third, proliferators can concurrently use a declared facility and a small, clandestine facility. Figure 13.1 shows three possible scenarios and Table 13.1 is a brief description for these scenarios.



[*] Unsafeguarded LEUF6 can be provided to GCEPs if proliferators diverted Non-UF6 LEU from other nuclear facilities and converted them at a uranium conversion facility.

Figure 13.1 HEU Production Tactics and Nuclear Material Flow

Table 13.1 Three Scenarios to Produce HEU

Scenario Name[685]	Types of Facilities Used	Process
Break-out	Only declared GCEP	(1) Material provision (both NUF_6 and $LEUF_6$) -Illicit acquisition of undeclared material -Material diversion from other nuclear facilities -Material diversion within the GCEP (2) Operation: off-design operation
Sneak-out	Only clandestine GCEP	(1) Material provision (both NUF_6 and $LEUF_6$) -Illicit acquisition of undeclared material -Material diversion from other nuclear facilities (2) Operation: clandestine operation
Concurrent sneak-out	Concurrent use of declared and clandestine GCEPs[686]	(1) Material provision -LEU diversion from declared GCEPs (2) Operation: two steps -LEU production at declared GCEPs -HEU production at clandestine GCEPs

685 International Institute for Strategic Studies (IISS), *Iran's Strategic Weapons Programmes : A Net Assessment, IISS Strategic Dossier* (London, UK: Routledge, 2005)., pp.53-57.
686 Friend, "Urenco's Views on International Safeguards Inspection". URENCO sees this as unfeasible because to produce undeclared LEU for nuclear weapons is too complicated compared to other scenarios.

13.2.1 Scenario A: Break-out Scenario

Under the break-out scenario, proliferators produce HEU at a declared LEU-producing GCEP. The break-out scenario involves both political and technological issues. The fundamental technological question is whether a GCEP designed to produce LEU can be used for producing HEU. The facility can be modified in such a way as to redirect SWUs from the production of relatively large quantities of LEU to the production of much smaller quantities of HEU by diverting feed to a HEU-producing GCEP.

It is highly unlikely that a proliferator can produce HEU at a declared GCEP without being detected by IAEA inspectors under IAEA safeguards, especially under HSP-type safeguards or the Additional Protocol (AP). It is a general notion that proliferators assume their illicit activities will eventually be detected and are willing to face opposition from the international community.

The IISS (2005) study details this scenario into "direct break-out" and "indirect break-out" depending on the Uranium Enrichment Ratio (UER) of the feed used: a direct scenario uses LEU feed and an indirect scenario uses NU feed. [687] The use of LEU feed ($LEUF_6$) can shorten the period required to produce HEU significantly as compared to NU feed.

13.2.2 Scenario B: Sneak-Out Scenario

The sneak-out scenario is where proliferators use only clandestinely-built GCEPs to produce HEU in the absence of any declared GCEPs within the countries. As reviewed in Chapter 12, the construction of a declared GCEP is not generally accepted as possible in the current NPT regime.[688] However, this scenario may not be the only option, but may be attractive for countries that do not have a pre-existing declared GCEP. With current detection technology, it is almost impossible to detect clandestine GCEPs in a straightforward fashion, as reviewed in Chapter 11.

From proliferators' standpoint, the operation of a clandestine GCEP will be much more expensive than the break-out scenario.[689] Proliferators need measures to hide environmental signatures associated with the operation of the facility. However, this scenario can be more economical than Scenario A because sanctions from the international community will be avoided as long as a proliferator is able to keep their actions hidden unless this facility is detected by safeguarders.

13.2.3 Scenario C: Concurrent Sneak-Out Scenario

The concurrent sneak-out scenario is where proliferators utilize both declared and clandestine GCEPs. This scenario may be attractive in that the advantages of break-out and sneak-out scenarios can be selectively adopted. In this case, a declared GCEP can be used for two purposes; i) a means to gain

[687] International Institute for Strategic Studies (IISS), *Iran's Strategic Weapons Programmes : A Net Assessment.*, p.55.

[688] The construction of sensitive nuclear facilities is not generally allowed according to Article IV of the NPT. However, the interpretation of the NPT article IV is under dispute.

[689] International Institute for Strategic Studies (IISS), *Iran's Strategic Weapons Programmes : A Net Assessment.*, p.57.

technology, equipment and material for building clandestine GCEP, and ii) as a cover for distracting the attention of the international community from building clandestine GCEP.

The former scenario can proceed as follows: First, proliferators legally build and operate a declared GCEP and show a good level of compliance with the IAEA safeguards. Second, proliferators clandestinely build a small footprint of undeclared GCEP in order to produce HEU exclusively. This will take shorter time than to build only a clandestine GCEP because proliferators could use experience accumulated through the operation of a declared facility.

In the case of the second scenario, the construction of this clandestine GCEP does not need to be sequential and can be in parallel with the declared facility. This can be made possible if proliferators build a GCEP just focus the international community's attention on the declared construction operations and away from the clandestine operations.

Some perceive this scenario is too complicated to be successful.[690] Friend (2007) argues that the sneak-out scenario is much simpler and less detectable than this complicated scenario. Under this scenario, proliferators can significantly reduce the time required to produce HEU because proliferators can stockpile $LEUF_6$ from the declared GCEPs.[691] The recent case of a second Iranian GCEP in the city of Qom can be categorized as this scenario.

13.3 Break-out Scenario From a Political Perspective

13.3.1 Legal Loopholes Favorable to Break-out Scenario

In this section, possible loopholes that can be exploited by proliferators through abrogating the NPT are reviewed. Proliferators may join the NPT with the goal of obtaining nuclear technology important to nuclear weapons program. Figure 13.2 and Table 13.2 describe important requirements concerning the timeline of the NPT and IAEA safeguards.

[690] Friend, "Urenco's Views on International Safeguards Inspection".

[691] Albright and Shire, "A Witches' Brew? Evaluating Iran's Uranium-Enrichment Progress," review of Reviewed Item, no. For a break-out scenario, approximately 700-800 kg of 4 per cent enriched LEU would be required to be able to produce 20-25 kg of weapons-grade uranium.

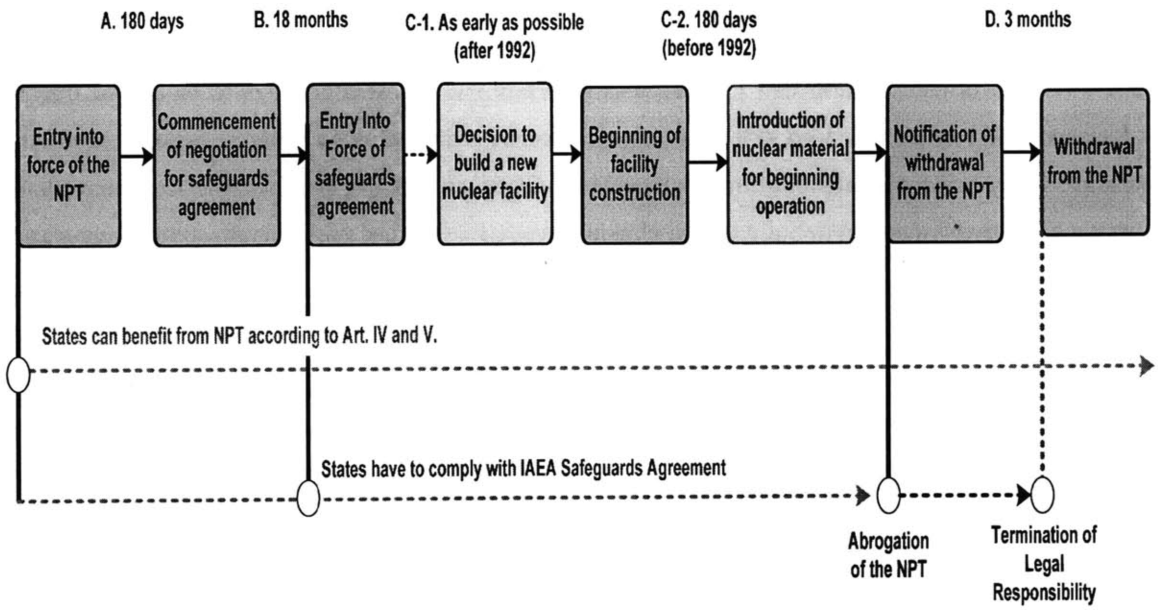


Figure 13.2 Important Requirements for Time in the NPT Regime

After proliferators have obtained relevant nuclear technology, they can withdraw from the NPT by simply sending notification to the NPT and the United Nations Security Council (UNSC). But, the UNSC does not have the legal power to reject a withdrawal notification by abrogators. These create several problems as follows: First, it is highly likely that the initiation of taking benefits from the NPT begins upon the signing of the NPT by states, whereas states' legal responsibilities begin with the conclusion of safeguards agreements between the IAEA and a state. Second, the requirement of information provision about a new nuclear facility depends on the content of subsidiary arrangements between the IAEA and a state. Third, even if states withdraw from the NPT, there seems to be no provision to decommission already-built nuclear facilities or to destroy already-acquired resources.

Table 13.2 Important Timeliness Regarding Nuclear Proliferation of Iran in the NPT Regime

Time	Activity / information	Reference	Duration	Description
A	Negotiation of agreements with IAEA	NPT III-4	180 days	• Negotiation of such agreements shall commence within 180 days from the original entry into force of this Treaty.
B			18 months	• Such agreements shall enter into force not later than 18 months after the date of initiation of negotiations.
C-1	Design information on construction of a new facility: Safeguards Agreement	INFCIRC/153 (1971)	N/A	• Design information in respect of new facilities shall be provided within the time limits to be specified in the ***subsidiary arrangement, and*** as early as possible before the introduction of nuclear material. [Para 42. of INFCIRC/153]
		INFCIRC/214 (1974)	N/A	• INFCIRC/214 is based on INFCIRC/153 – Article 42 is as paragraph 42 noted above. • Iran had not accepted the obligation of IAEA BOG's decision in 1992.
C-2	Design information on construction of a new facility: Subsidiary Arrangements	Subsidiary Arrangements prior to IAEA BOG decision of December 1992	180 days [b]	• The initial Subsidiary Arrangement of each state with the IAEA said by ***180 days before*** the introduction of nuclear material. • Iran's Subsidiary Arrangements contained this provision. (May 15, 1974)
		IAEA BOG decision of December 1992 [a]	As soon as	•. The IAEA Board of Governors asked all states to provide information about the design of a new facility ***as soon as*** the ***decision to construct or to authorize*** construction was taken.[c]
		Revised Subsidiary Arrangements of Iran	As soon as	• Iran concluded amended subsidiary arrangements in 2003, accepting the 1992 IAEA BOG's decision by an exchange of letters. [d] • Iran unilaterally sought to revoke the amendment in 2007.[692]
D	Withdrawal from the NPT	Article X of NPT	3 months	• A member state to the NPT that wants to withdraw can withdraw from the NPT by notifying the Treaty and the UNSC ***three months*** in advance.

Notes
[a] GOV/2554/Att.2/Rev.2; GOV/OR/777. Paras. 74-76. [Dec.12, 1992)
[b] Mark Hibbs makes an incorrect statement that Iran has "60 days" requirement for the provision of information.[693]
[c] Paul Kerr refers to an incorrect statement that "Boucher (State Department Spokesman) added that all other states, with the exception of Iran, have accepted to provide complete information about a new facility about a new facility about a new facility no later than 180days before ***the start of construction***." [694]
[d] IAEA GOV/2003/40, Implementation of the NPT safeguards agreement in the Islamic Republic of Iran Report by the Director General (Paras. 6 and 15).

[692] James M. Acton, *Iran Violated International Obligations on Qom Facility* (Carnegie Endowment for International Peace, Sep 25 2009 [cited Oct 1 2009]).
[693] Mark Hibbs, "U.S. Briefed Suppliers Group in October on Suspected Iranian Enrichment," *NuclearFuel* 27, no. 26 (2002).
[694] Paul Kerr, " IAEA to Visit Two 'Secret' Nuclear Sites in Iran," *Arms Control Today* (January/February 2003).

13.3.2 Classification of Break-out Scenario

As previously reviewed, the IISS (2005) study divides the break-out scenario into direct break-out and indirect break-out, depending on whether proliferators use NUF6 or LEUF6 feed. In this work, break-out scenarios are classified into an aggressive break-out scenario and a defensive break-out scenario. These are based on the timeline when proliferators declare the withdrawal from the NPT.

Table 13.3 Classification of Break-out Scenarios

Criteria	Scenario Name	Description	Reference
UER of Feed	Direct	Use NUF_6 as feed for HEU production	IISS (2005)
	Indirect	Use $LEUF_6$ as feed for HEU production	
Proliferator's Posture	Aggressive	Declare withdrawal from the NPT at the same time with the start of HEU production	
	Defensive	Hide or deny HEU production activities until it is confirmed by the IAEA	

A. Aggressive Break-out Scenario (short-duration scenario)

The aggressive break-out scenario means that proliferators declare withdrawal from the NPT at the time when they begin break-out activities. It is highly likely that proliferators have sufficient confidence that they can produce HEU in a very short duration after the launch of break-out scenario and before the initiation of sanctions or punishment from the international community. In order to do so, proliferators should have either a GCEP of large SWU capacity or stockpiled-LEU as feed. The short duration of time required for this scenario would permit proliferators to produce nuclear weapons before the international community takes any measures, and thus, renders the NPT regime largely ineffective.

B. Defensive Break-out Scenario (long-duration scenario)

Te defensive break-out scenario can be chosen by proliferators when either (a) they want to hide their nuclear weapons programs as long as possible, which may be until the successful production of sufficient HEU or (b) when they think that they could sufficiently delay the IAEA's dealing with proliferation activities. In general, if proliferators are able to accomplish the break-out plan before the international sanctions become practically effective, the plan remains still attractive and successful. Thus, proliferators may continue their defensive break-out scenario until they are sanctioned by the UNSC.

13.3.3 Setup of Time Plan

Proliferators should have an elaborate plan for break-out scenario based on the estimated time required to produce HEU considering both the SWU capacity of the facility and the UER of the feed material in order to launch the break-out scenario. [695] The plan should include a technological plan for eluding IAEA's safeguards measures and a political plan for delaying the international community's response after discovery. When a proliferator seeks the break-out scenario, it is the hope that the production of HEU may not be detected until the desired quantity has been obtained.[696] Thus, it is critical to estimate when nuclear proliferation activities will be detected because it will decide the available time to produce HEU until international sanctions are practically effective.

The overall time framework for the break-out scenario considering interaction between safeguarders and proliferators is described in Figure 13.3. From a proliferator's standpoint, it is important to determine when critical Decision Points (DPs) take place throughout the entire scenario. Critical DPs include the decision to break-out, launch of the break-out scenario, possible detection of break-out, withdrawal from the NPT, and completion of the break-out plan.

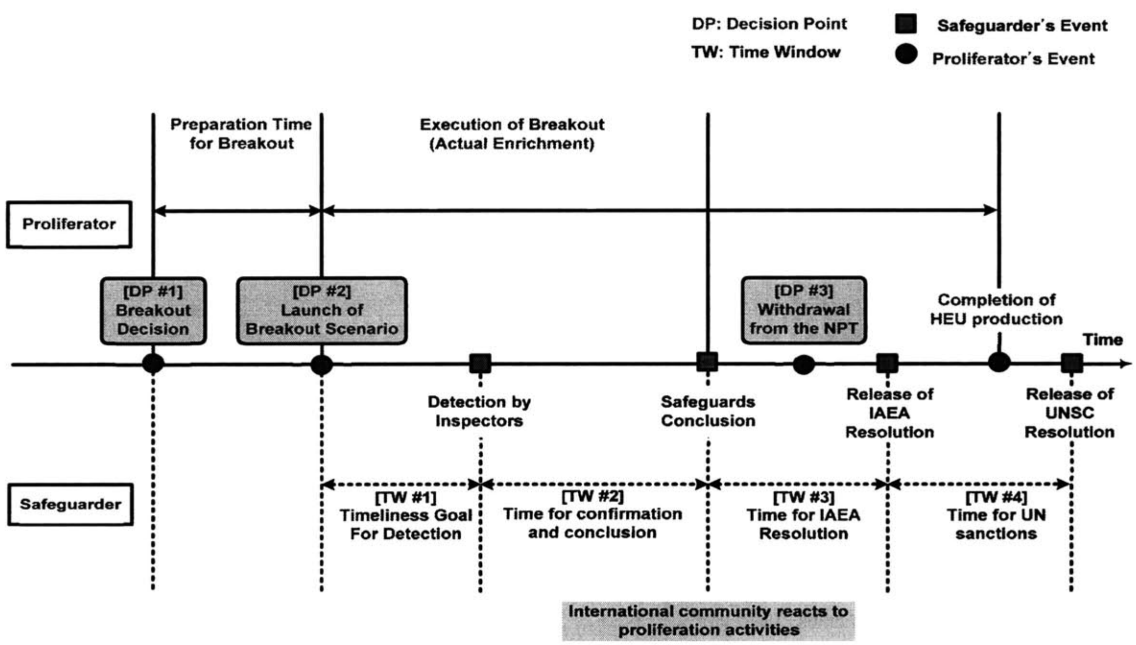


Figure 13.3 Possible Timeline under Break-out Scenario

[695] International Institute for Strategic Studies (IISS), *Iran's Strategic Weapons Programmes : A Net Assessment.*, p.53.

[696] The IAEA's timeliness goal for detection of undeclared production of HEU is set to one month. W. Bush et al., *IAEA Experience with Environmental Sampling at Gas Centrifuge Enrichment Plants in the European Union, IAEA-SM-367/10/04* (2004)..

From a safeguarders' point of view, time framework can be divided into four Time Windows (TWs) for response to proliferation activities: Time for detection of break-out, time for confirming the existence of break-out, time for issuing IAEA resolutions, and time for drawing UNSC resolutions. Historically, the NPT regime has neither been very effective nor swift in responding to the break-out scenario of proliferators. Thus, it is highly likely that proliferators can establish the plan for the break-out scenario in a way that minimizes the required time for HEU production, giving little time for the international community to respond.

Proliferators can set different time objectives for success of the break-out scenario, thereby requiring different amount of resources as shown in Figure 13.4. Based on this figure, proliferators can develop tactics in order to extend each period by delaying safeguarders' response as listed in Table 13.4. The scenario that completes for period #1 is the most threatening scenario 'in which a proliferator diverts uranium from declared facilities right after the inspection is over and then complete the production of HEU before the next inspection falls' and is named a crash-through scenario.[697]

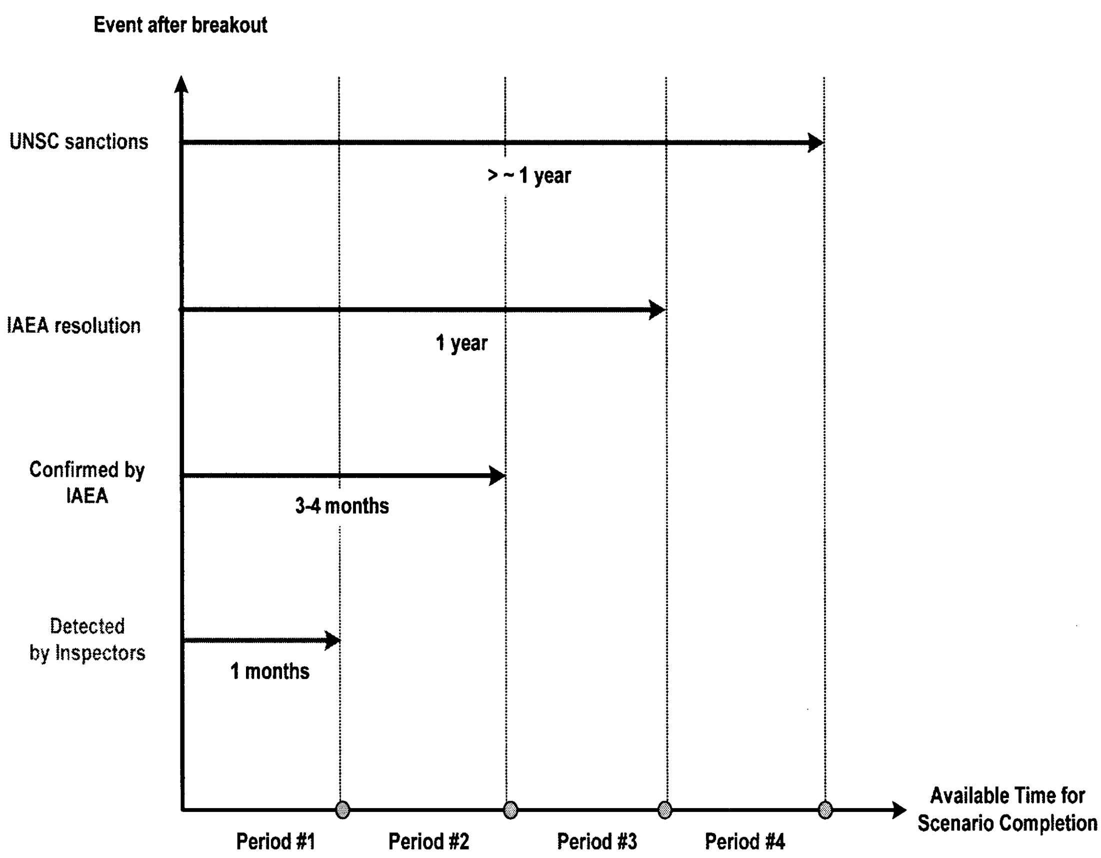


Figure 13.4 Different Levels of Objectives for Break-out Scenario[698]

[697] Bragin, Carlson, and Leslie, "Building Proliferation-Resistance into the Nuclear Fuel Cycle".
[698] The duration of each period is based on the author's subjective assumption.

Table 13.4 Tactics to Delay Safeguarders' Response for Break-out Scenario

Period	How each period can be delayed?	Key factors
#1	• Proliferators may start with refusing to allow IAEA inspections because the refusal of inspections does not necessarily imply that HEU is produced. • Proliferators make a compromise between the time required to produce HEU and the risk of being detected.	Length of non-inspection period
#2	• It takes about at least 3-4 months for the IAEA to obtain the result of destructive assay for environmental samples due to lack of resources.	IAEA's resources
#3	• The IAEA will try to solve the issue with the state concerned before it refers the case to the UNSC.	The IAEA BOG's resource
#4	• Even if suspicious proliferation activities are detected by the IAEA, the IAEA should wait until it is able to provide concrete evidence about the existence of proliferation activities in order to refer the case to the United Nations Security Council (UNSC). • Proliferators may threaten to withdraw from the NPT in order to deter the UNSC from imposing sanctions. • Some of permanent members of UN Security Council are not willing to impose sanctions through UNSC resolutions.	International community's consensus

Note: From technological point of view, it takes about three months to get accurate results through Destructive Assay (DA) from swiped samples.

13.4 Break-out Scenario from Technical Perspective

GCEPs designed for LEU production can vary its operation to follow the demand of clandestine HEU production facilities. Figure 13.5 shows how such diversion could take place in five possible off-design operation modes. The batch recycling mode, Figure 13.5 (a), is the only method that does not require the modification of the configuration of cascades. Only the first four approaches can be used to produce weapons-grade uranium. The valve adjusting mode, Figure 13.5 (e), cannot be used to produce weapons-grade HEU because this option has a limitation that the highest UER that can be obtained is only 20 percent.

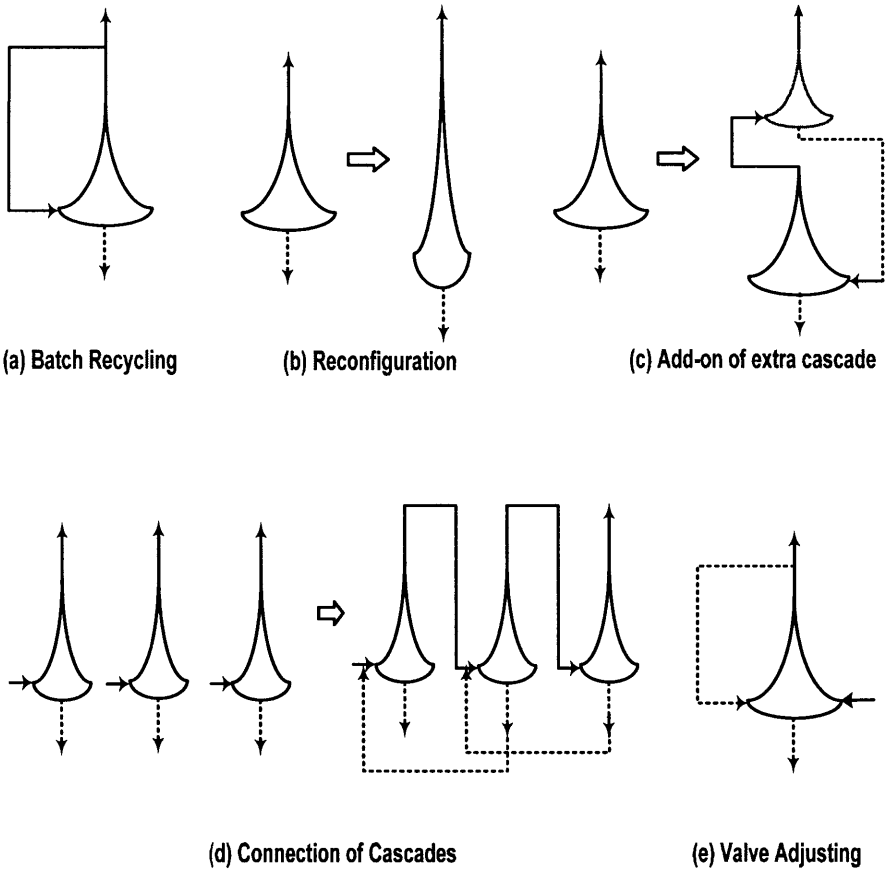


Figure 13.5 Tactics to produce HEU at declared LEU GCEP

13.4.1 Batch Recycling

In the batch recycling mode, the cascade product is fed back into the same cascade for subsequent cycles of enrichment without any change in the configuration of cascade. In a GCEP, feed of any UER can be used. However, proliferators should go though the recycling process until the desired enrichment ratio of product is achieved. The maximum value of the product enrichment ratio at each pass of batch recycling can be calculated under the condition of a total reflux, which is given by:

$$N_{P,\max} = \alpha^2 N_F. \qquad (13.1)$$

where N_P is product assay, N_F is feed assay, and á is overall design enrichment factor.[699]

[699] Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation.*, p.116.

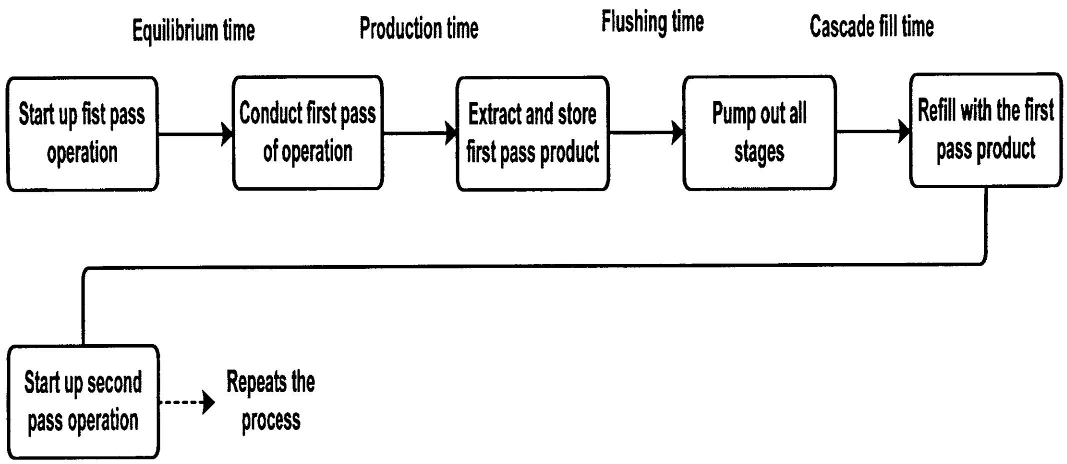


Figure 13.6 Process for Batch Recycling Operation

A typical process for conducting a batch recycling operation is shown in Figure 13.6. In order to recycle the output, the process should be repeated until product with the expected UER is achieved. Proliferators can start batch recycling operation within a matter of days after decision is made to conduct illicit operations. However, this option is considered very inefficient for HEU production because of the high time costs associated with these operations and poor use of valuable uranium feed resources.[700] The batch recycling process requires iterative HEU production processes, which will require additional enrichment time. In this regard, an equilibrium time is the dominant factor to decide whether batch recycling is a viable option.[701]

In general, a batch recycling operation is a simple and fast option because it does not require any modification of cascades.[702] Three to four passes are considered sufficient to produce HEU from LEU production facilities. As a result, the implementation of this option can be completed quickly and minimizes the risk of timely detection by safeguarders and associated reactions from the international community.[703]

The batch recycling mode is very inefficient for HEU production because of the high time cost and inefficient use of uranium feed for the following reasons: First, the plant must be shut down and all stages must be evacuated, refilled with new feed, and then restarted.[704] Even though there is no visual change in cascade configuration, the batch recycling mode is not free from detection due to the

[700] Kemp and Glaser, *The Gas Centrifuge and the Nonproliferation of Nuclear Weapons*.
[701] Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation*., p.20.
[702] International Nuclear Fuel Cycle Evaluation, *Enrichment Availability, Report of INFCE Working Group 2* (Vienna, Austria: IAEA, Mar. 1980)., p.131.
[703] Kemp and Glaser, *The Gas Centrifuge and the Nonproliferation of Nuclear Weapons*.
[704] Personal communication with Dr. Charles Forsberg, Mar. 5 2009. Stopping and restarting operation in gas centrifuge is extremely sensitive process from mechanical point of view. During batch recycling operation, even though the plant stops enrichment operation, it is still running in vacuum state of centrifuges. i.e., it does not stop completely.

operational changes.[705] Second, this option can only be chosen if enough uranium material is available. The UER of tails assay increases as the number of passes increases; therefore, large quantities of enriched UF_6 are discarded. This makes detection more likely because the stripping step of the cascade remains the same, but the UER of feed increases with each pass.[706] Third, this option would require special material transport equipment for the storage of product to avoid fission criticality limitations. This is because enriched product should be stored before the next pass after each pass of batch recycling operation.[707]

13.4.2 Reconfiguration

Reconfiguration requires the total restructuring of a current cascade or building more cascades in a manner that increases the total number of enrichment stages. Generally, cascades can be reconfigured from few stages-many parallel (or long-width) elements to many stages-small parallel (short-width) elements, i.e., a cascade or several cascades is reconfigured into a narrower, but longer assembly.[708] This requires considerable time to complete the re-piping process and to prepare to operate in reconfigured-mode for re-piping process. In addition, cascades need to be shut down for reconfiguration and this procedure subjects the machines to high levels of stress that may result in machine failure. Regardless, reconfiguration mode is the most effective way of producing HEU for long-term operation.[709] In particular, the use of manifolds with in-built valves enables cascades to be reconfigured without obvious external indicators.

13.4.3 Add-on of Modular Extra Cascades: Use of Undeclared SWU

This option is to use undeclared additional cascades within declared GCEPs. The two ways to use add-on cascades are as follows:

- **Undeclared cascades within the facility**

  The proliferator could have additional cascades within the facility, but not inside cascade halls, which are declared to the IAEA. Under this scenario, after LEU is produced inside cascade hall, the LEU product is transferred using cylinders to the undeclared subsequent cascade within the

[705] International Nuclear Fuel Cycle Evaluation, *Enrichment Availability*., p.131.
[706] Roughly, three times more LEU feed is required than through operation in reconfiguration mode. R. Scott Kemp and A. Glaser, *Statement on Iran's Ability to Make a Nuclear Weapon and the Significance of the 19 February 2009 IAEA Report on Iran's Nuclear Enrichment Program* (2009 [cited May 5 2009]); available from http://www.princeton.edu/~aglaser/2009glaser_iran.pdf. Bukharin (2002) suggests that a GCEP designed to produce 3 percent LEU can produce 90 percent HEU in approximately four cycles. Bukharin, "U.S.-Russian Bilateral Transparency Regime to Verify Nonproduction of HEU.", pp.211-221.
[707] International Nuclear Fuel Cycle Evaluation, *Enrichment Availability*. , p.131.
[708] Oleg Bukharin (2002) suggests that approximately 20 stages are required to produce HEU with current technology; R.S. Kemp and A. Glaser (2007) argue that even for a first-generation centrifuge, a series of 30-40 stages are enough to produce HEU; The Safeguards Options Study (1995:p.90) proposes 60 stages are required.
[709] Kemp and Glaser, *Statement on Iran's Ability to Make a Nuclear Weapon and the Significance of the 19 February 2009 IAEA Report on Iran's Nuclear Enrichment Program.*

facility but located in restricted areas under the CSA-type subsidiary arrangements. Under the AP, the proliferator can use "managed access".

- **Undeclared cascades inside cascade halls during non-inspection period**

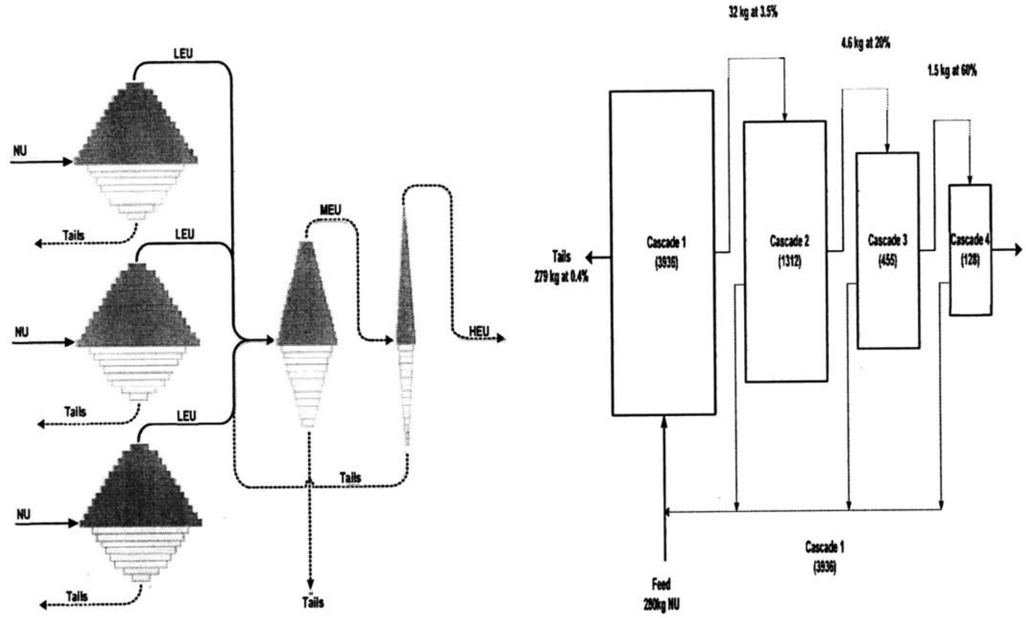
Proliferators can simply add an additional modular cascade on top of a pre-existing cascade. To prepare this option, additional centrifuges to form an extra cascade and additional floor area to put an extra cascade in place are required. In addition to extra preparation efforts, this option requires longer 'equilibrium time' and has some criticality constraints during operation. This option takes longer to accomplish than reconfiguration or batch recycling.

13.4.4 Connection of Cascades: Cascade Interconnection

Modular plant design is one mode of construction of GCEPs. A GCEP typically consists of a large number of cascades that operate in parallel with each producing LEU product. If proliferators rearrange the parallel-operating cascades used for LEU production into a series-operation of several cascades, HEU can be produced. This can be accomplished by resetting piping to connect pre-existing cascades that were previously disconnected. This option is sometimes called the "***parallel-overlap***" mode operation and may involve partial reconfiguration.[710] This configuration will allow proliferators to use a portion of the plant to produce HEU while producing legitimate LEU product in the rest of the facility.[711] Similar to the scenario above, instead of connecting different cascades, UF6 cylinders can be used to transfer the product to the subsequent cascade.

Cascades can be arranged to produce HEU through connection of cascades; these arrangements are shown Figure 13.7. At declared GCEPs, there should be several cascades to produce a large amount of LEU of same enrichment level or sometimes to produce different enrichment levels of LEU. These cascades can be connected and can produce HEU without a significant change in cascade design. The success of this mode would depend on the size and number of cascades and the specific design features of the plant. [712]

[710] Kemp and Glaser, *The Gas Centrifuge and the Nonproliferation of Nuclear Weapons*.
[711] Bukharin, "U.S.-Russian Bilateral Transparency Regime to Verify Nonproduction of HEU."
[712] International Nuclear Fuel Cycle Evaluation, *Enrichment Availability*., p.131.



(a)Parallel-Overlap Mode (b) Interconnection in Series

Figure 13.7 Examples of Cascade Interconnection[713]

13.4.5 Valve Adjusting: Cascade Flow Adjustment

If a valve setting is adjusted in a way that a portion of the product is returned to the feed point of a cascade the UER of the product could be increased about by 20 percent. In other words, this option is a way to increase product assay at the expense of the product withdrawal rate. However, this option is not feasible for directly producing weapons-grade uranium because of the limitation in enriching uranium up to only 20%. This option is one scenario to produce uranium that can be easily diverted to weapons-grade uranium in combination with either clandestine facilities or other options. This option is performed at the expense of the efficiency of cascade operation. [714]

13.4.6 Possible Combination of Five Off-Design Modes

It is highly unlikely that a proliferator can seek more than one of five off-design operation modes. However, E.A. Hakkila et al., (1995) suggested that batch recycling and connection of cascades can be combined. [715] This combination may be selected to take advantage of two scenarios while minimizing their weaknesses. These weaknesses include (a) the top cascade would run out of material

[713] Figure (a) from International Institute for Strategic Studies (IISS), *Iran's Strategic Weapons Programmes : A Net Assessment.*, p.44; figure (b) from A. Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation," *Science and Global Security* 1 (May 2008)., pp.1-25. Figure 8, p.19 The Libyan Enrichment Project. The numbers in parenthesis stand for the number of centrifuge machines.

[714] Bukharin, "U.S.-Russian Bilateral Transparency Regime to Verify Nonproduction of HEU."

[715] E.A. Hakkila et al., *The Safeguards Options Study.*

in the connection of cascades mode; and (b) the first pass requires a long operation time in the batch-recycling mode. Production time required for HEU would decrease by combining these two scenarios.

13.5 Evaluation on Off-Design Operation Modes under Break-out Scenario

13.5.1 Comparison

The research focused on the evaluation of the feasibility for each option discussed here has identified key pros and cons of these options, which are outlined in Table 13.5. All references in the Table 13.5 include batch recycling as the only option that does not require the modification of cascades. Modification of cascades can incur mechanical damage to centrifuges that result in inefficiency which cannot be modeled in a simple fashion. In this regard, it is generally believed that the batch recycling option is highly likely to be chosen by proliferators.

Table 13.5 Evaluation for Proliferation Application

Option	Pros	Cons	References
Batch recycling	No need to modify facilities	Requires three times more input than reconfiguration	[a] [b][c][d]
Reconfiguration	High efficiency in operation	Takes substantial time to reconfigure cascades	[a][b][d]
Add-on	Simple modification, if GCEPs are modularized.	Requires additional construction and thus takes longer to accomplish than reconfiguration or batch recycling.	[a] [d]
Interconnection	Simple modification, if GCEPs have several cascades.	Connection of several cascades	[d]
Cascade Flow Adjusting	No need to modify facility	20 percent enrichment is the maximum limit	[d]

Notes
[a] David Albright and Jacqueline Shire (2007) [716]
[b] R. Scott Kemp and Alexander Glaser (2009)[717]
[c] Gregory S. Jones (2008)[718]
[d] O. Bukharin (2002)[719]

[716] Albright and Shire, "A Witches' Brew? Evaluating Iran's Uranium-Enrichment Progress," review of Reviewed Item, no.
[717] Kemp and Glaser, *Statement on Iran's Ability to Make a Nuclear Weapon and the Significance of the 19 February 2009 IAEA Report on Iran's Nuclear Enrichment Program.*
[718] Jones, *Iran's Centrifuge Enrichment Program as a Source of Fissile Material for Nuclear Weapons.* He considers two main classes of scenarios for a break-out in Iran: using a clandestine enrichment plant from either LEU stock or from natural uranium.
[719] Bukharin, "U.S.-Russian Bilateral Transparency Regime to Verify Nonproduction of HEU."

Table 13.6 shows quantitative values for each option. Cascade interconnection is the most time efficient method for HEU production. However, this operation mode requires at least three cascades to execute for LEU, MEU, and HEU production.

Table 13.6 Reference Data and Indicators for Each Option[720]

Scenario	Min. cascades required	Enrichment achieved	Required time for 25 kg HEU	Affecting factors	Indicators	Detection Possibility
Cascade Flow Adjustment	1	20 %	5 yrs	Reflux ratio	Valve setting [d]	Moderate
Batch Recycling	1	90 % (4 passes)	2.6 yrs [a]	Throughput	•Valve settings •Reduced plant throughput	Moderate [d]
Reconfiguration	1	90 %	7.5 months [f]	•Plant design [b] •Maintenance requirement •Throughput	•Piping modifications •Unauthorized activities	The highest detection probability
Combination	7	90 % (2 passes)	4.5 months	Throughput	•Valve settings and tubing	Moderate
Cascade Interconnection	3	90 %	4 months	Throughput	•Header pipe modification •Tubing to service connections	Moderate
Add-on	2	90 %	N/A	Modularity of cascade	•Valve settings •Additional space	High

Notes

[a] Passes 3 and 4 would take only one month. Kemp and Glaser (2009) estimate that it would take about eight months with a 4,000 machine-cascade. (6 months to produce LEU and 7 weeks to process the LEU into HEU.)

[b] Plant design includes gas manifolds, appropriate valves, interplant piping.

[c] Non-routine setting: Values that are normally closed will be open, and valves that are normally open will be closed.

[d] The most significant reduction in throughput, containment of HEU particles on all process equipment.

[e] FA, R, B/R can produce HEU by isolating only one cascade.

[f] Kemp and Glaser (2009)'s estimate is 'over 6 months', whereas IISS (2009)'s estimate is less than '6 months'[721]

[720]E.A. Hakkila et al., *The Safeguards Options Study.*, p.95. Table 7-V, indicators and detection probabilities from pp.87-96.

[721] Kemp and Glaser, *Statement on Iran's Ability to Make a Nuclear Weapon and the Significance of the 19 February 2009 IAEA Report on Iran's Nuclear Enrichment Program.*; David Albright, Paul Brennan, and

The following conclusions can be drawn for all options: First, the size of the plant is important. The larger capacity of the GCEP allows proliferators to produce the larger the amount of LEU or HEU. This is because of the isolation of a cascade would represent a small portion of the overall throughput. Thus, in a large plant, proliferators can make use of statistical uncertainty to hide their activities. Second, it is obvious that reduced plant throughput, and an HEU presence, would result in an increase in radiation levels. Finally, all scenarios involve the use of portable feed and withdrawal (F/W) systems, and would require the presence of extra cylinders.[722]

13.5.2 Technical Overview of Batch Recycling Mode

This section reviews the quantification of the batch recycling mode for producing HEU. The batch recycling mode has been chosen for quantitative analysis two reasons: First, it seems to be the easiest option because it does not include any modification of cascades; second, the quantification of the cascade modification process is very complex and entails a lot of uncertainty.

The main focus of quantification studies has been to calculate the time necessary for producing the required amount of weapons-grade uranium for making one nuclear warhead. It should be noted that there are many variations in the results because of uncertainties which include individual gas centrifuge machine capacity, mass or enrichment ratio of fissile material based on technology, required time to reconfigure or equilibrium time and cascade fill time to recycle, decrease in efficiencies from configuration change, and feed in different UERs. In the calculation, the required time to produce HEU is affected by several factors and is a function of SWU throughput, selected mode of off-design operation, feed assay, tails assay, etc. Furthermore, gas centrifuge machines of the same design can produce different SWU capacity, depending on the level of operational skill of the operators.

A. Increase in UER for Each Pass in Batch Recycling

The production as a function of product availability and time spent within each batch in a recycling operation is presented in Table 13.7. The UER of the product increases exponentially with the number of passes. For example, it takes around 95 days for proliferators to produce 20 kg of WGU for making a nuclear bomb with feed of 4.8 % LEU.[723]

Jacqueline Shire, *Nuclear Weapon Breakout Scenarios: Correcting the Record* (Mar. 18 2009 [cited June 3 2009]); available from http://www.isisnucleariran.org/assets/pdf/Correcting_the_Record.pdf.

[722] The Safeguards Options Study (1995), p.96.

[723] Jones, *Iran's Centrifuge Enrichment Program as a Source of Fissile Material for Nuclear Weapons*.

Table 13.7 UER Increase of Product Per Pass at GCEPs with P-1 Design

Reference	Glaser [2008]		Jones [2008]		
Scenario	Direct Break-out		Indirect Break-out		
GCEP Capacity	164-machine cascade (250-300 SWU/yr) [a]		3,000-machine cascade (7,500 SWU/yr)		
Enrichment Passes	Feed assay	Product assay	Feed assay	Product assay	Time required
1st	NU	3.498 %	-		-
2nd	3.498 %	16.30 %	4.8 % (1780 kg)	26.2 % (206 kg)	70 days [b]
3rd	16.30 %	91.089 %	26.2 % (201 kg)	71.4 % (47 kg)	16 days
4th	-		71.4 % (42 kg)	94.6 % (20kg)	7 days

Notes
[a] The performance of Iran's machine may vary between 1.5 SWU/yr and 2 SWU/yr.[David Albright et al., 2009]
[b] The initial pass requires longer operating time than the following passes.
[c] Two days are considered for equilibrium and cascade fill time between before the next pass begins.
[d] 5 kg of feed loss is assumed during feed/withdrawal process.
[e] In general, it is assumed that about 6,000 SWU is required for producing enough HEU to make one nuclear bomb per year.

B. Relationship among Various Factors Affecting Time Required for HEU Production

Options A and B in Table 13.8 describe the impact of the concentration of trails on the mass of product and the time required for producing WGU product. Given that proliferators want to produce the same UER product, there is a compromise which balances the required time against the mass of the product. Option C shows the potential advantage of an indirect break-out scenario which uses stockpiled LEU for input. Under this configuration it only takes 8 days for proliferators to produce 25 kg of WGU from feed of 3.55% LEU.

Table 13.8 Impact of Feed and Tails Assay on Time Required to Produce 25 kg 93% HEU[724]

Option	Feeds		Concentration of	Product		Time
	UER	Mass	Tails	UER	Mass	Required
A	NU (0.71%)	150,000 kg	0.3%	93%	654 kg	1 year
B	NU (0.71%)	150,000 kg	0.65 %	93%	100 kg	40 days
C	NU (0.71%)	150,000 kg	0.2%	4%	20,000 kg	1 year
	LEU (4%)	20,000 kg	3.55%	93%	100 kg	8 days

Note: These are values for a reference facility with a capacity of 130tSWU/yr.

724 Linear relationship is assumed between feed masses and products. Original input feed that Glaser assumed 150,000 kg of natural uranium but linearly divided by to calculate HEU required for making one nuclear bomb. Data is excerpted from Glaser, *Making Highly Enriched Uranium*, A. Glaser, *Making Highly Enriched Uranium* (4th) (Princeton University, Feb. 26 2007 [cited Oct. 18 2008]); available from www.princeton.edu/~aglaser/lecture2007_makingheu.pdf

Based on Table 13.8, a simple causal-loop diagram can be drawn as shown in Figure 13.8. The larger the SWU capacity of a GCEP, UER of feed, concentration of tails, the shorter the time required to produce a Significant Quantity (SQ) of HEU.

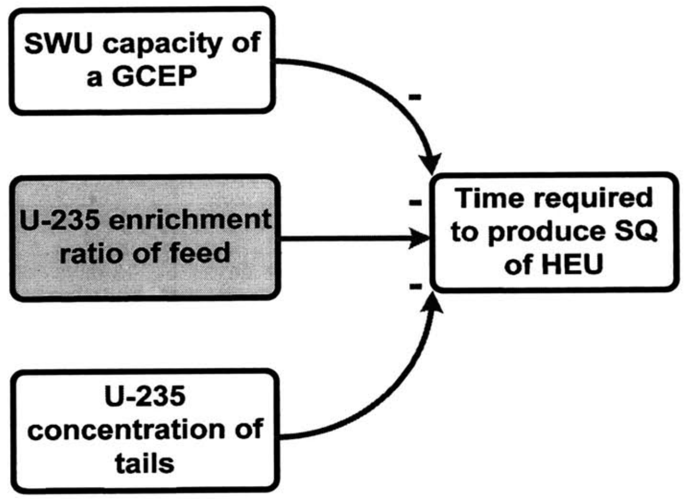


Figure 13.8 Factors Affecting Time Required to Produce HEU in B/R mode

C. Comparison between Batch Recycling and Reconfiguration

A recent study by Jones (2008) analyzed a possible break-out scenario in a batch recycling mode quantitatively focusing on Iran's uranium enrichment program.[725] Jones provided enrichment data in terms of total time required based on several scenarios with different SWU capacities and different levels of enriched uranium as an input. IISS (2005) performed a similar study but it focused on reconfiguration mode. Table 13.9 is the summary of the research findings from Jones and the IISS. Options A, B, and C in Table 13.9 represent indirect break-out in batch recycling, indirect break-out in reconfiguration, and direct break-out reconfiguration, respectively. If options A and B with 3,000 gas centrifuge machines are compared roughly (this is because Jones (2008) does not provide the concentration of tails), the reconfiguration mode can produce HEU in about one-half the time required for batch recycling.[726] This effect significantly increases as the SWU capacity of a GCEP increases.

[725] Jones, *Iran's Centrifuge Enrichment Program as a Source of Fissile Material for Nuclear Weapons.*

[726] For further discussion on the comparison of required times between batch recycling and reconfiguration with regard to Iran's program, see Albright, Brennan, and Shire, *Nuclear Weapon Breakout Scenarios: Correcting the Record.*;Kemp and Glaser, *Statement on Iran's Ability to Make a Nuclear Weapon and the Significance of the 19 February 2009 IAEA Report on Iran's Nuclear Enrichment Program.*

Table 13.9 Time Required to Produce HEU from Feeds of Different Enrichment Ratios

Reference		Jones (2008)	IISS (2005)			
Operation Mode		**Batch Recycling**	**Reconfiguration**			
Fissile Material		20 kg of 93.1% HEU	25 kg of 93% HEU			
Option		**A** [a]	**B** [b]		**C** [c]	
Feed assay		4.8% LEU feed	5% LEU feed		NU feed	
Tails assay		-	0.4 %	0.2 %	0.4 %	0.2 %
No of machines	**164**	-	1.8 yrs	2.4 yrs	13.6 yrs	17 yrs
	1000	-	108 days	143 days	2.2 yrs	2.7 yrs
	3000	95 days	36-48 days	48 days	271 days	330 days
	10000	37 days	-		-	
	20000	24 days	-		-	
	50000	17 days	2-3 days	3 days	16 days	20 days

Notes
[a] Gregory S. Jones (2008), p. 7
[b] IISS (2005), Iran's Strategic Weapons Programs: a net assessment, Table 2A, p.55
[c] IISS (2005), Table 1A. p.54
[d] P.1 Centrifuge technology is assumed for both cases; however, 2.5 SWU and 2 SWU are assumed for capacity per centrifuge for Jones and IISS, respectively.

13.6 Summary

Possible scenarios available to proliferators to produce HEU were analyzed in this chapter. These scenarios were break-out, sneak-out, and concurrent sneak-out, depending on the types of GCEPs involved in HEU production. The break-out scenario seems the most feasible and most abundant in the literature; thus, the break-out scenario was analyzed from both political and technical perspectives.

Technically, there are five off-design operation modes to divert a LEU-producing GCEP to a HEU-producing GCEP. Each way has pros and cons and different time and mass requirements for HEU production. Though an exact evaluation is limited because of the limitation in experimental data and modeling tools, a rough estimate was made using available literature.

Each scenario requires different approaches from safeguarders' point of view. To deter break-out and concurrent scenarios effective and efficient IAEA safeguards systems are necessary. Early detection of proliferation activities will provide more time to the international community to take political actions. Under the sneak-out scenario, the IAEA's typical safeguards approach cannot be applied because of either limited or no access to the suspect facilities. Thus, other means to get around this problem should be developed, which include improvement of remote detection technologies, as reviewed in Chapter 11. It should be noted that all of these scenarios are both technological and political.

CHAPTER 14 QUANTITATIVE ANALYSIS OF MODEL

14.1 Introduction

This chapter is dedicated to the practical application of an integrated methodology for evaluating proliferation scenarios focused on production of HEU at GCEPs. Three proliferation scenarios for HEU production at GCEPs were developed in Chapters 12 and 13. In this chapter, the three scenarios were translated into success trees and were quantitatively analyzed. Top event probability values were calculated using Saphire® by using input values for all basic events in the success trees. This quantitative analysis is challenging due to the inherent competition of proliferator and safeguarder resources and their affect on the probabilistic outcome. Two main methods were employed to evaluate the basic events. Expert opinion elicitation was obtained for a quantitative study. Alternatively, a hierarchic metrics-index method was developed to more completely understand the competition between safeguarder and proliferators. Lastly, three types of quantitative analysis were completed as were uncertainty analysis, sensitivity analysis, and importance analysis. Together, these analysis methods provide insight to the state of proliferation and safeguards currently utilized.

14.2 Success Tree for Nuclear Weapons Program

A simple success tree for an entire nuclear weapons program is shown in Figure 14.1. Some of these steps occur in parallel, whereas other steps occur sequentially.

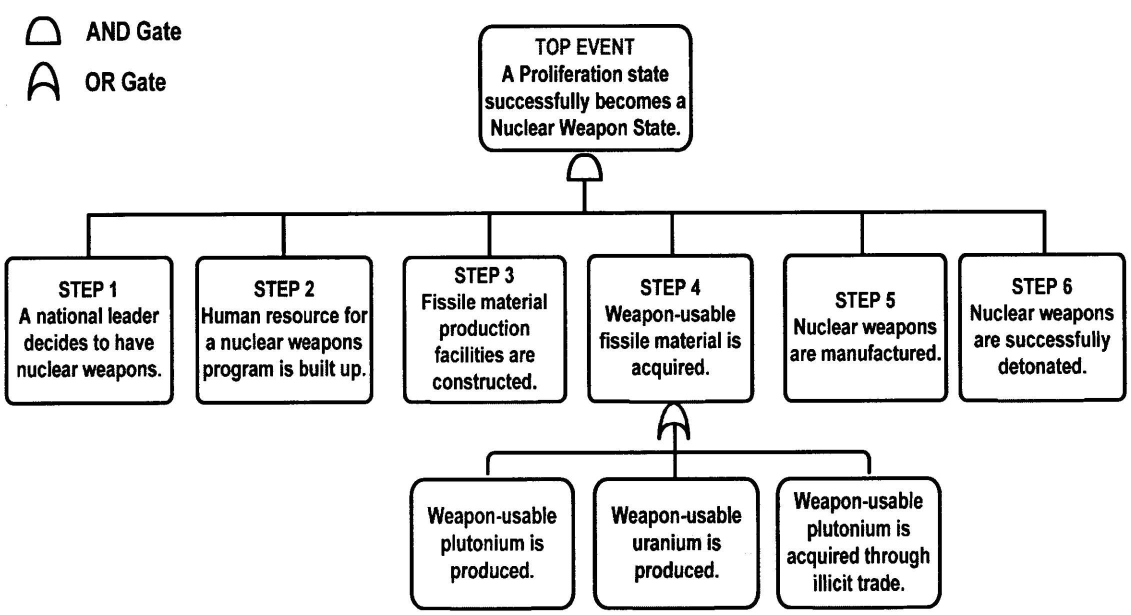


Figure 14.1 Success tree for Nuclear Weapons Program

A success of each step can be represented as an event with probabilistic values. Thus, the success probability of the top event can be expressed as:

$$\Pr(Top\ Event) = \Pr(Step\,1)\cdot\Pr(Step\,2)\cdot\Pr(Step\,3)\cdot\Pr(Step\,4)\cdot\Pr(Step\,5)\cdot\Pr(Step\,6) \quad \cdots (14.1)$$

Among the six steps necessary to the success of nuclear weapons programs, only weapons-usable uranium acquisition at step 4 was modeled and analyzed using the integrated methodology in this study.

14.3 Logical Chart for HEU Production

Before success trees can be constructed, logics that lead to the success of the top event need to be prepared as narrative scenarios. These logics were developed based on the scenarios identified previously in Chapters 12 and 13. A logical chart used for building success trees in this work is shown in Figure 14.2.

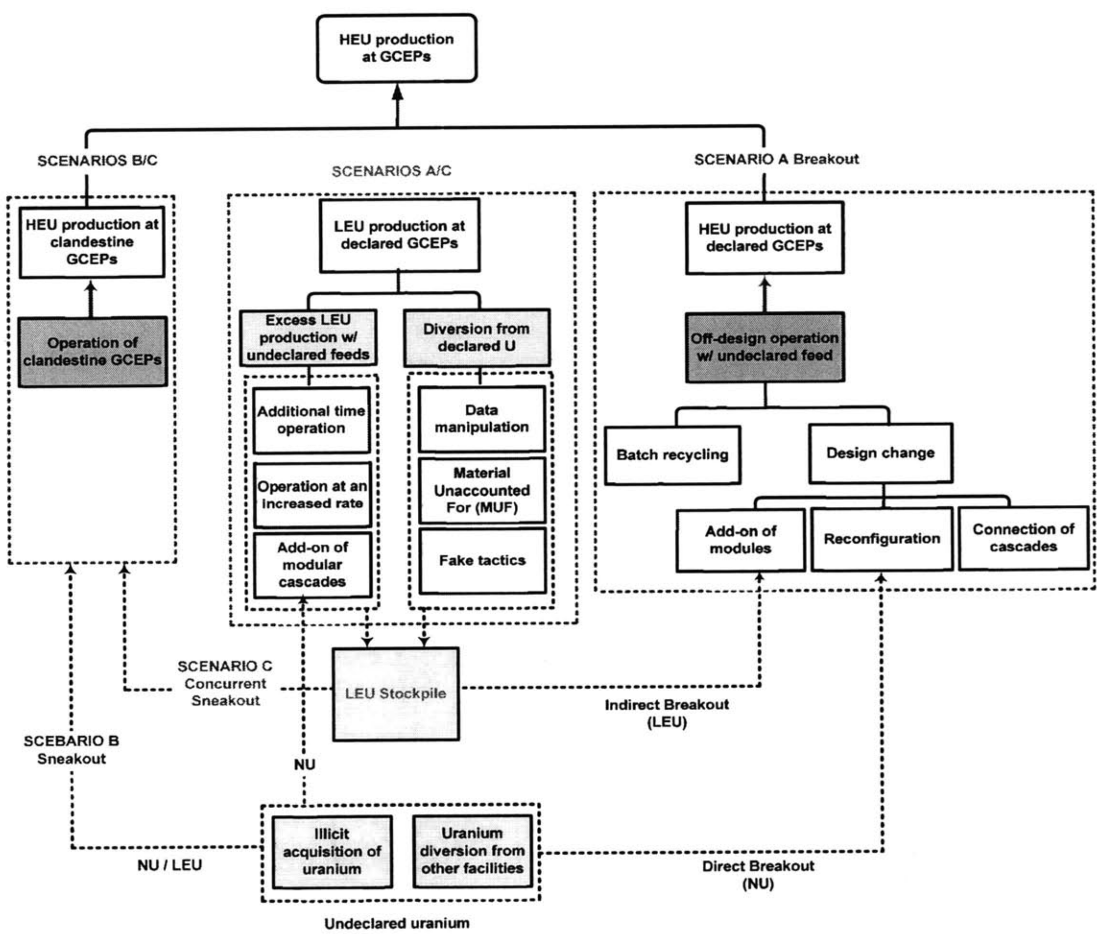


Figure 14.2 Logical Chart for Establishing Success Trees

14.4. Success Trees for HEU Production

A top event is defined as successful production of HEU by proliferators at GCEPs. As previously described, HEU production can be achieved either through clandestine facilities, declared facilities, or both. The success trees were structured as the intersection of two activities: (i) nuclear material is provided to the facilities and (ii) a GCEP is operated to produce HEU. All events in the success trees are described as "proliferation activities are not detected" for confronting the problem in a more structured manner.

In reality, the detection of proliferation activities does not necessarily mean that HEU production activities can be stopped. Nuclear weapon production is a technological and political issue and this work only address the detection (technological) aspect, not the political arena. But, the method used here to describe basic events is reasonable in the sense that the detection of proliferation activities will trigger responses from the international community, which may significantly delay proliferators' proliferation plan.

Close attention should be given to defining assumptions on the basic events due to their effect of affecting the outcome of the analyses. First, two conditions should be met in order for basic events to occur: (i) proliferators attempt to carry out a basic event and (ii) safeguards activities did not detect the proliferation activities. However, it is assumed that all proliferators have an intention to proliferate; thereby, making the probability attempted proliferation a certainty. Thus, the probability of "Proliferators attempt to carry out a basic event" can be treated as unity. Second, it should be noted that probability values of basic events are the results of the competition between safeguarders and proliferators.

14.4.1 Scenario A – Break-out Scenario using only Declared GCEPs

A. Material Preparation

In the case of "direct" break-out scenario, proliferators do not need to stockpile LEU so that they can use uranium out of declared inventory. It is a reasonable assumption that a generic declared GCEP has at least several Significant Quantities (SQs) of uranium, though the exact amount of inventory is dependent on the capacity of the plant. In the case of "indirect" break-out scenario, the proliferators need to stockpile LEU while searching for a proper time to conduct "break-out." There are two ways to stockpile LEU: production of excessive LEU using undeclared feed and skimming LEU product using Material Unaccounted For (MUF).

B. Operating a Facility for Producing HEU

As reviewed in Chapter 13, there are four possible modes of off-design operation for producing HEU at a GCEP that is optimized to produce LEU. It is general opinion that only one option may be chosen for HEU production because each option requires a substantial effort to carry out. However, all four modes can be employed simultaneously if the plant has sufficient capacity, despite the likelihood this will not occur.

C. Success Tree and Basic Events

A success tree for the break-out scenario was established in a way that includes all types of nuclear facilities and all possible diversion scenarios. It should be noted here that within the tree the state can operate both declared and clandestine Uranium Conversion Facilities (UCFs), which provides a high degree of freedom in diverting non-UF6 form of uranium.

For the quantitative study, two basic events were not considered: NU (Non-UF6) is not diverted from CANDU reactors and NUF6 is diverted from a GCEP feed. This is because these two events are highly unlikely for uranium-based nuclear weapons programs. The success tree for scenario is shown in Figure 14.3 and the basic events in the success tree are listed in Table 14.1.

Table 14.1 Basic Events in Scenario A

BE	Activity	Description	Scenarios
A1	U illicit acquisition	NU illicit acquisition is not detected.	All
A2		*LEU illicit acquisition is not detected.*	
A3		NUF6 illicit acquisition is not detected.	
A4		LEUF6 illicit acquisition is not detected.	
A5	U diversion	*NU provision via diversion from NU FFP is not detected.*	All
A6		*NU provision via diversion from CANDU is not detected.*	
A7		LEU provision via diversion from LEU FFP is not detected.	
A8		LEU provision via diversion from LWRs is not detected.	
A9		NU diversion from the declared UCF is not detected.	A,C
A10		*NUF6 diversion within the declared GCEP is not detected.*	
A11		LEUF6 product diversion within the declared GCEP is not detected.	
A12	Clandestine UCF	Clandestine UCF operation is not detected by ESWA/LIDAR at short distances.	All
A13		Clandestine UCF operation is not detected by ESWA/LIDAR at long distances.	
A14	Declared UCF	Undeclared NU conversion at declared UCF is not detected.	A, C
A15		Undeclared LEU conversion at declared UCF is not detected.	
A16	Excess LEU production	Excess LEU production with add-on modular cascades is not detected.	A, C
A17		Excess LEU production at additional time is not detected.	
A18		Excess LEU production at an increased production rate is not detected.	
A19	HEU production	HEU production in "batch recycling" mode is not detected.	A only
A20		HEU production in "reconfiguration" mode is not detected.	
A21		HEU production in "connection of cascades" mode is not detected.	
A22		HEU production with "add-on modular cascades" is not detected.	

Note: Basic events in *italic* were not considered for quantitative study because of their high unlikelihood.

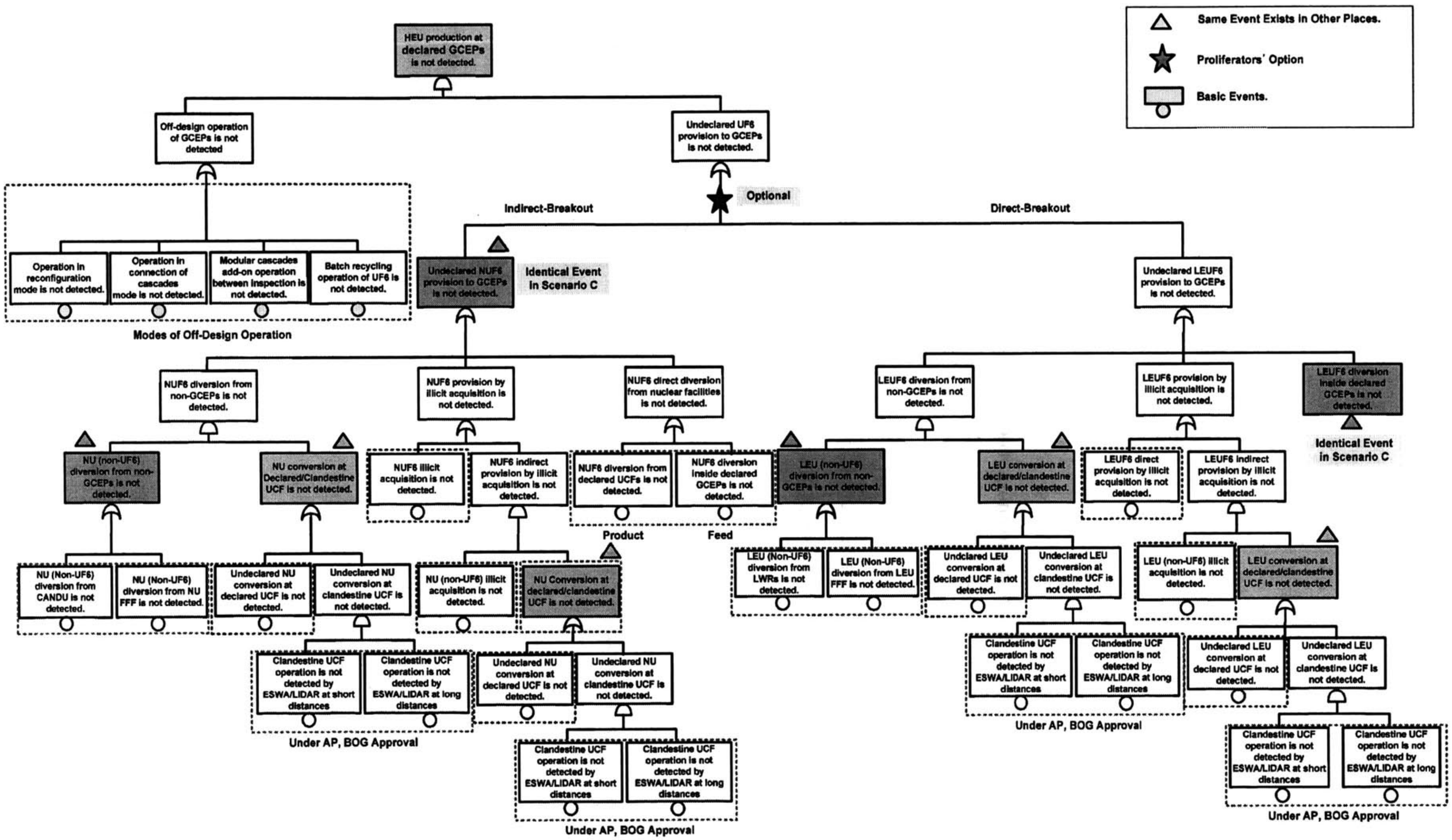


Figure 14.3 Success Tree for Scenario A

14.4.2 Scenario B- Sneak out Scenario using Only a Clandestine GCEP

A. Material Preparation

The most critical aspect for successful operation of a clandestine GCEP is the method in which undeclared uranium feed is provided. The opportunities to obtain undeclared material increase when the state has a large total capacity of nuclear facilities. As shown in Figure 14.2, undeclared uranium can be acquired in two ways: illicit acquisition and diversion from other nuclear facilities.

B. Operating a Facility for Producing HEU

Proliferators with optimized cascades for HEU production at a clandestine GCEP do not need to modify plants as would be required for declared nuclear facilities. However, in order to continue operation of a clandestine GCEP without detection, proliferators may employ various subterfuge tactics such as air filter for reducing atmospheric effluents, camouflage to hide thermal and optical signatures.

C. Success Tree and Basic Events

A typical IAEA safeguards approach cannot be applied for detecting the sneak-out scenario. Instead, remote detection technologies should be used. In establishing this success tree, detection of declared UCFs operation was not considered because they cannot claim to the IAEA why they need UCFs without having declared GCEPs. Three types of detection technologies were reflected in the success tree. First, Environmental Sampling over Wide Area (ESWA) was considered for detecting both a clandestine GCEP and a UCF. Second, Differential Absorption LIDAR (DIAL) was considered for detecting HF that may be released from GCEPs, and Raman scattering-based Light Detection and Ranging (LIDAR) was considered for detecting UF_2O_2 from UCFs. The use of satellite imagery was considered for only GCEPs because this technology seems to be of no use in detecting clandestine UCFs. It should be noted that ESWA, DIAL, and LIDAR cannot be used without the approval of Board of Governors (BOG) under the Additional Protocol (AP), as reviewed in Chapters 6 and 7. The success tree for scenario is shown in Figure 14.4 and the basic events in the success tree are listed in Table 14.2.

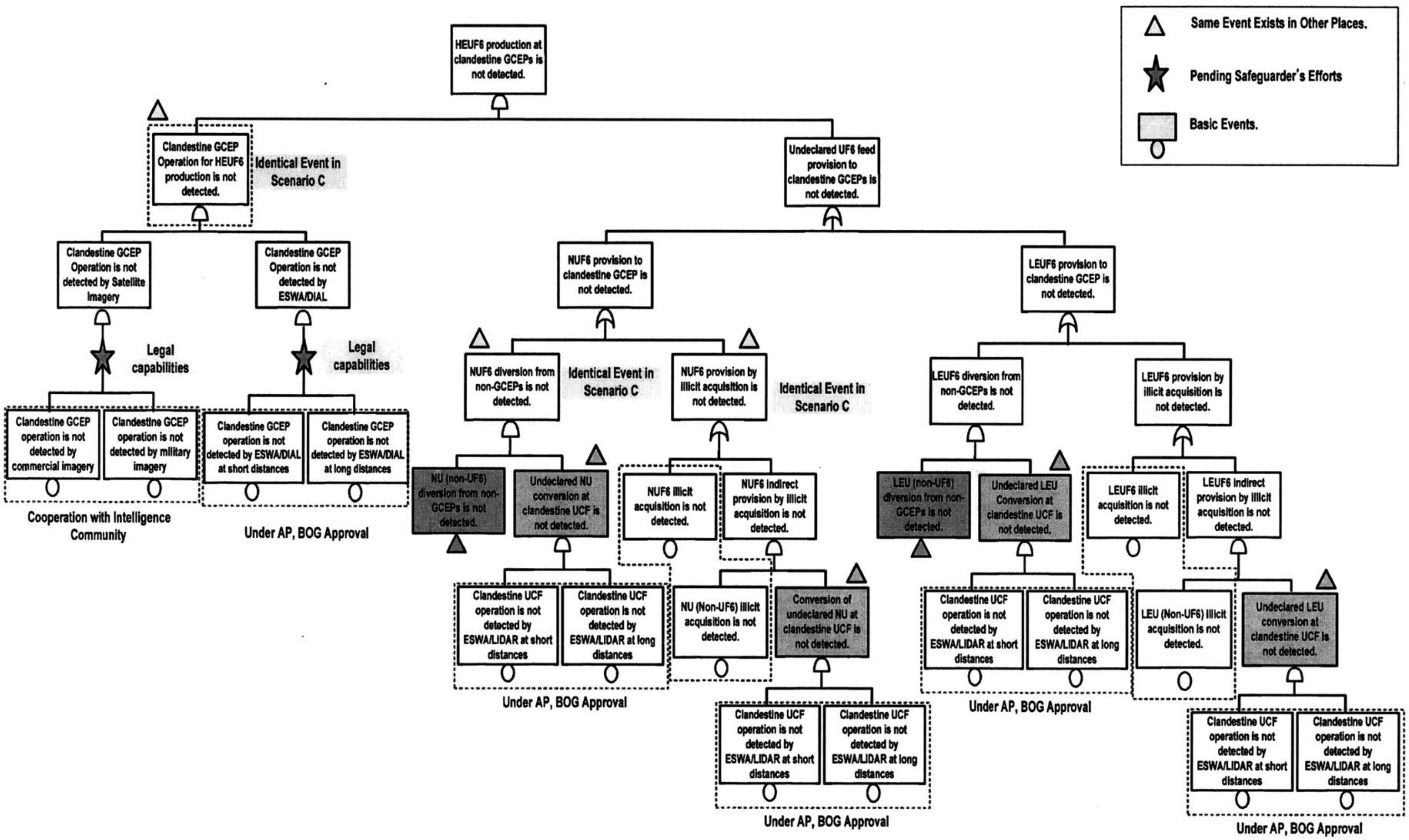


Figure 14.4 Success Tree for Scenario B

Table 14.2 Basic Events in Scenario B

BE	Activity	Description	Scenario
B1	U illicit acquisition	NU illicit acquisition is not detected.	All
B2		*LEU illicit acquisition is not detected.*	
B3		NUF6 illicit acquisition is not detected.	
B4		LEUF6 illicit acquisition is not detected.	
B5	U diversion	*NU provision via diversion from NU FFP is not detected.*	All
B6		*NU provision via diversion from CANDU is not detected.*	
B7		LEU provision via diversion from LEU FFP is not detected.	
B8		LEU provision via diversion from LWRs is not detected.	
B9	Clandestine UCF	Clandestine UCF operation is not detected by ESWA/LIDAR at short distances.	All
B10		Clandestine UCF operation is not detected by ESWA/LIDAR at long distances.	
B11	Clandestine GCEP	Clandestine GCEP operation is not detected by ESWA/DIAL at short distances.	B,C
B12		Clandestine GCEP operation is not detected by ESWA/DIAL at long distances.	
B13		Clandestine GCEP operation is not detected by commercial satellite imagery.	B,C
B14		Clandestine GCEP operation is not detected by military satellite imagery.	

Note: Basic events in *italic* were not considered for quantitative study because of their high unlikelihood.

14.4.3 Scenario C-Concurrent Sneak-out Scenario Using Declared and Clandestine GCEPs

A. Material Preparation

Material preparation for a declared GCEP is the same as in scenario A. Under this scenario, LEUF6 produced at a declared GCEP will be transferred to a clandestine GCEP. The declared GCEP serves as a LEU provider to the clandestine GCEP. It is assumed that LEUF6 intended for the clandestine GCEP is provided only through the operation of the declared GCEP. Such a scenario minimizes the probability of detecting a proliferator's activities. Thus, diversion of LEU from LWRs and LEU FFP, and illicit acquisition of LEU was not considered because of high detection probabilities of those events in the present study.

B. Operating a Declared GCEP and a Clandestine GCEP for Producing HEU

Operation of the declared GCEP is intended to produce LEUF6 and the produced LEUF6 will be diverted to produce HEU at clandestine GCEPs. It is also possible that a proliferator may operate multiple GCEPs to increase the probability of successfully diverting LEUF6. The operation of a clandestine GCEP is identical to scenario B. However, the capacity of the clandestine GCEP can be much smaller than that of scenario B. This is because the clandestine plant will use LEU for feed, which significantly reduces SWU and time requirement to produce HEU than NU feed.

C. Success Tree and Basic Events

The success tree for scenario C is the combination of success trees for scenarios A and B. The main difference between scenarios B and C is that uranium feed for a clandestine GCEP is confined to LEUF6 produced from a declared GCEP. Considering the difficulty with obtaining LEUF6 through illicit acquisition and substantial reduction in required time to produce HEU with LEU feed, this scenario may be promising. The success tree for scenario is shown in Figure 14.5 and the basic events in the success tree are listed in Table 14.3.

Table 14.3 Basic Events in Scenario C

BE	Group	Description	Scenario
C1	U illicit acquisition	NU illicit acquisition is not detected.	All
C2		NUF6 illicit acquisition is not detected.	
C3	U diversion	*NU provision via diversion from NU FFPs is not detected.*	All
C4		*NU provision via diversion from CANDU is not detected.*	
C5		NUF6 diversion from UCF is not detected.	
C6		*NUF6 diversion within the declared GCEP is not detected.*	A, C
C7		LEUF6 product diversion within the declared GCEP is not detected.	
C8	Clandestine UCF	Clandestine UCF operation is not detected by ESWA/LIDAR at short distances.	All
C9		Clandestine UCF operation is not detected by ESWA/LIDAR at long distances.	
C10	Declared UCF	Undeclared NU conversion at declared UCF is not detected.	A, C
C11	Excess LEU production	Excess LEU production with add-on modular cascades is not detected.	A, C
C12		Excess LEU production at additional time is not detected.	
C13		Excess LEU production at an increased production rate is not detected.	
C14	Clandestine GCEP Operation	Clandestine GCEP operation is not detected by ESWA/DIAL at short distances.	B, C
C15		Clandestine GCEP operation is not detected by ESWA/DIAL at long distances.	
C16		Clandestine GCEP operation is not detected by commercial satellite imagery.	B, C
C17		Clandestine GCEP operation is not detected by military satellite imagery.	

Note: Basic events in *italic* were not considered for quantitative study because of their high unlikelihood.

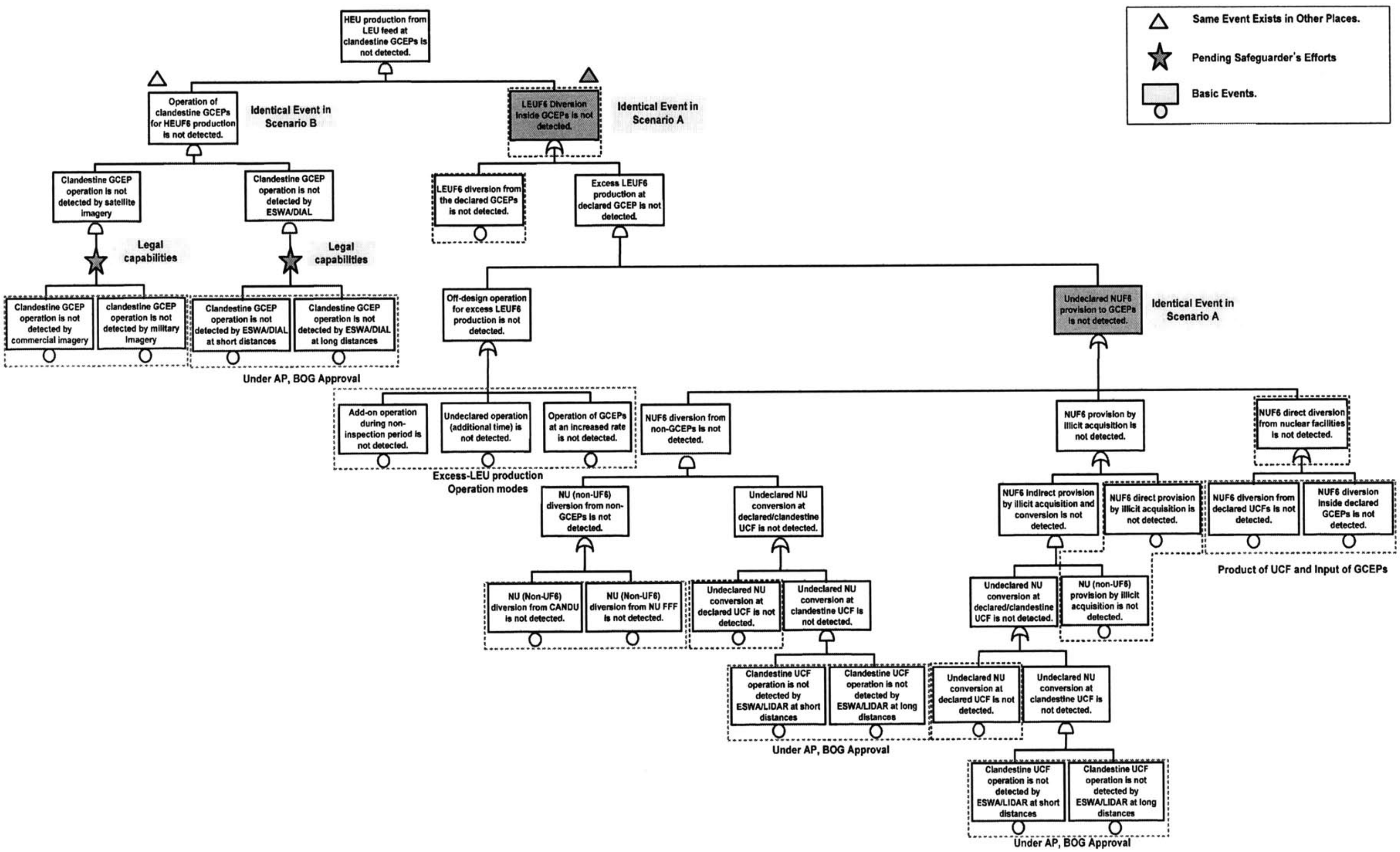


Figure 14.5 Success Tree for Scenario C

14.5 Categorization of Basic Events

From the success trees developed for HEU production at declared and clandestine GCEPs, basic events were grouped into five categories and are shown in Table 14.4. This grouping will facilitate the quantitative evaluation for basic events.

Table 14.4 Categorization of Basic Events from Success Trees

Category	Detection	Description
Category I	Operation of declared GCEPs and UCFs	· HEU production in off-design operation modes · Excess LEU production
		· Additional undeclared conversion operation at declared UCFs
Category II	Operation of clandestine GCEPs and UCFs	· Satellite imagery for detecting a GCEP
Category III		· ESWA/DIAL for detecting a GCEP
		· ESWA/LIDAR for detecting a UCF
Category IV	Uranium feed provision via diversion	· Diversion of uranium (non-UF6) from other facilities
		· Diversion of uranium feed (UF6) from GCEPs and UCFs
Category V	Uranium feed provision via illicit acquisition	· Illicit acquisition of uranium feed -UF6 form (NUF6, LEUF6) -Non-UF6 form (NU, LEU)

14.6 Basic Events Evaluation from Experts

Basic event probability values were obtained from industry and government experts for each of the categories listed in Table 14.4. Compilation of expert opinions provides a framework for determining more accurate probabilistic input values further depth for analysis of the results. The expert opinions were collected through a questionnaire for each category of experts. These questionnaires are provided in the Appendix I. The experts provided their evaluation for each specific time period from 1970s to 2010s as stated in Chapter 1.

Limited knowledge is available on detection of international uranium transfers, which corresponds to the expert opinion for Category V activities. Two factors greatly affecting detection are competing over time. First, a safeguards system for monitoring or detecting nuclear material transfer are continually strengthened, which makes detection more likely. Second, the chances of smuggling nuclear material may increase with the number of nuclear facilities.

14.7 Basic Event Evaluation from Hierarchic Metrics

Hierarchic metrics were developed to quantify which factors affect the probability values of basic events. A detection probability varies with capabilities or resources of two sides. As reviewed in Chapter 5, the NPT regime's capabilities can be divided into technological capability and legal capability. Thus, hierarchic metrics include all possible measures to detect a specific proliferation event. If data about previous detection events are available, theses metrics can be used to evaluate basic events in terms of probabilities. If each basic metric is assigned a score, a top measure is calculated with a proper structure function and can lead to an importance index through data processing. This index is further complicated because the IAEA's detection information is treated as classified material and used of these metrics for quantitative evaluation is limited. However, these metrics are useful for brainstorming what experts consider while formulating their expert opinions. In addition, these metrics will provide insight into how different features of a facility affect detection probability values by considering specific operational facility factor. These metrics are shown in Figures from 14.6 to 14.7. [See Appendix J for other metrics]

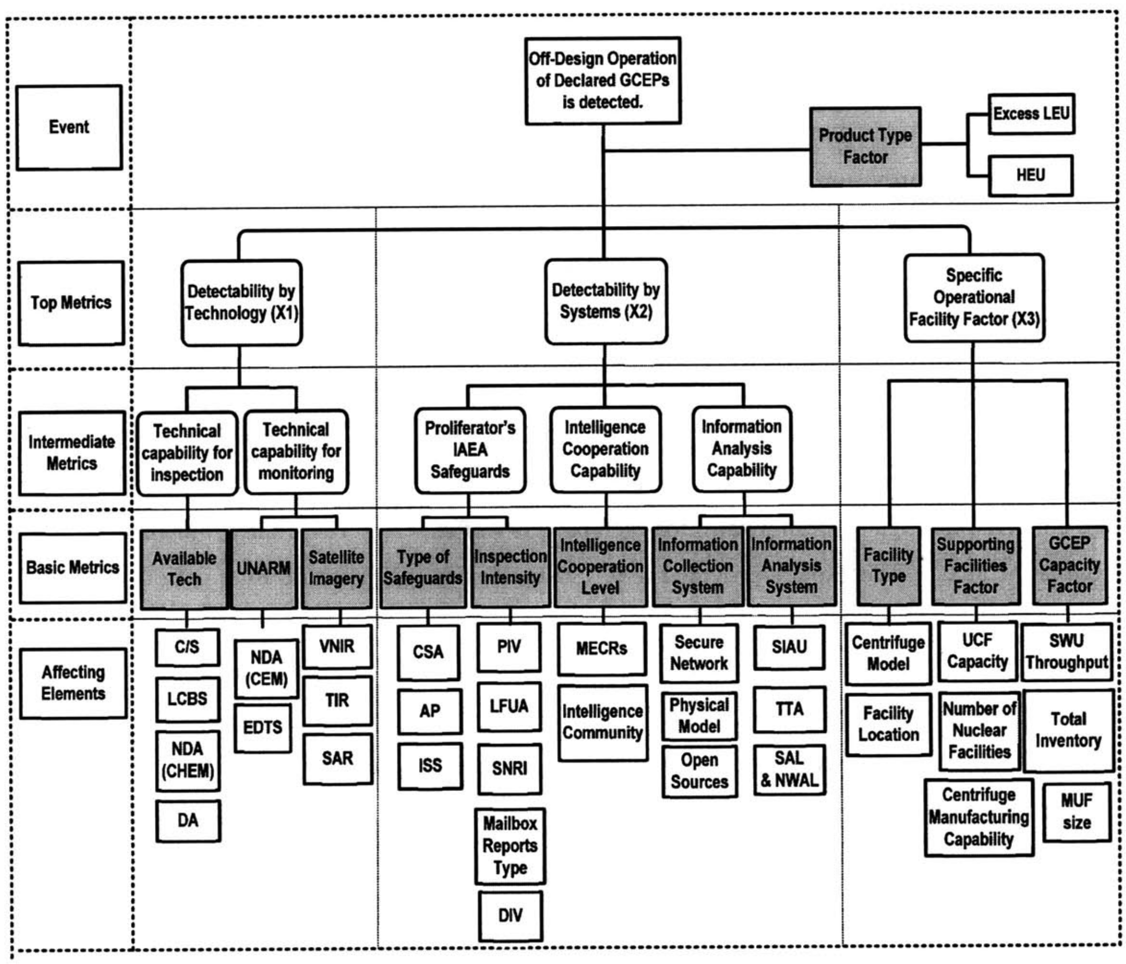


Figure 14.6 Hierarchic Metric for Detection of Off-Design Operation of GCEPs

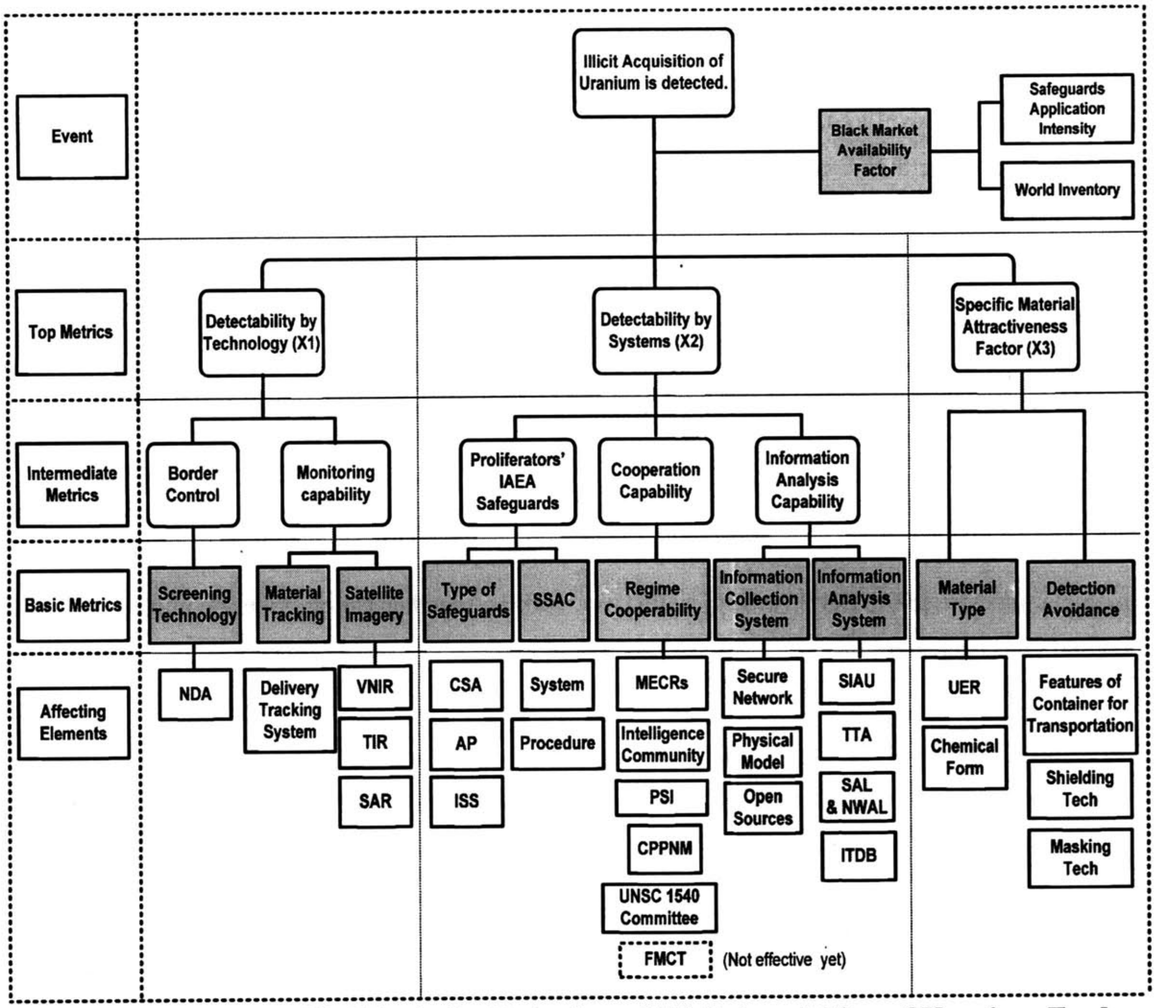


Figure 14.7 Hierarchic Metric for Detection of Illicit Acquisition of Uranium Feed

Table 14.5 Full Description of Acronyms in the Metrics

Acronym	Full Description	Acronym	Full Description
C/S	Containment and Surveillance	ISS	Integrated Safeguards System
LCBS	Load-Cell Based Weighing System	PIV	Physical Inventory Verification
NDA	Nondestructive assay	DIV	Design Inventory Verification
CHEM	Cascade Header Enrichment Monitor	MECR	Multilateral Export Control Regime
DA	Destructive Assay	SIAU	Satellite Imagery Analysis Unit
CEMO	Cascade Enrichment Monitoring	TTA	Nuclear Trade and Technology Analysis Unit
VNIR	Visual Near Infrared Imagery	SAL	Safeguards Analytical Laboratory
TIR	Thermal Infrared Imagery	NWAL	Network Analytical Laboratory
SAR	Synthetic Aperture Radar	UCF	Uranium Conversion Facility
CSA	Comprehensive Safeguards Agreement	MUF	Material Unaccounted For
AP	Additional protocol	SWU	Separative Work Unit

14.7.1 Applicability of Hierarchic Metrics for Input Values

In this section, applicability of hierarchic metrics without relying on expert evaluation for basic event quantification is explored. Input values for basic events can be determined, considering factors described in a hierarchic metrics and inserted into the model. Illicit acquisition of uranium feed is discussed using the Figure 14.7.

A. Relevant Literature: ITDB

The IAEA' Illicit Trafficking Database (ITDB) does not provide any information to "judge the extent to which the recorded incidents represent a potential security threat." The ITDB provides information about nuclear trafficking statics, which includes a total number of confirmed illicit trafficking accidents and the materials involved. However, the IAEA does not provide an estimation of the total number of unreported transfers. Much of the information processed by the IAEA was obtained through only member states to the ITDB. Thus, these factors working together can provide incomplete information on materials exchanges.[727]

B. Hierarchic Metrics

Two specific factors in Figure 14.7 were considered to determine input values. For simplicity, detection probability goals for each material type were used. Table 14.6 describes the two factors in detail.

Table 14.6 Descriptions for Factors used in Figure 14.7

Factors	Affecting elements	Description
Black market availability	**Safeguards application intensity**	**• Starting point of safeguards** -Is the specific type of uranium is subject to declaration by the CSA [Paras 33-35]? -Is the specific type of uranium is subject to declaration by the AP [Art. 2.a.(vi),(vii)]?
		• Exemption from safeguards -Can the specific type of uranium be exempted from safeguards [Paras 36-38]?
		• Reporting international transfers -Is the reporting of the international transfer of material under safeguards? [Para 34 (a)(b) CSA] -Is the reporting of the international transfer of material under safeguards? [Art. 2.(a)(ix), AP]
		• Nuclear Material Accountancy (NMA) Does the AP require detailed Nuclear Material Accountancy for the specific type of material? [Art.2(a), AP]

(Continued)

[727] IAEA, Illicit Trafficking Database, 2004.

Black market availability	**Safeguards application intensity**	• **Detection probability goals for material types** -HEU: a high detection probability (90%) -LEU: a medium detection probability (50%) -NU: a low detection probability (20%)
	World inventory	• How large is the estimated inventory of a specific type of uranium? • How many facilities produce the specific type of uranium? • How many facilities use the specific type of uranium? • How large is the total throughput of facilities that produce the specific types of uranium?
Material attractiveness	**Material type**	• How high is the U-235 enrichment ratio of the specific type of uranium? • How suitable is the composition and purity of the specific type of uranium for uranium enrichment operation?
	Detection avoidance	• Are the features of containers for transporting the specific type of uranium favorable for clandestine transportation? • How good is the level of proliferators' hiding technology that can evade safeguarders' technological detection system?

Considering all of these facts in Table 14.6, it could be a reasonable assumption that one can use detection probability goals for each type of material as detection probabilities for the illicit acquisition of different types of material. (i.e., a high detection goal means that material diversion is difficult.) This is because achieving a high detection goal leads to a high probability of detection and increased difficulty for illicit materials export.

14.8. Scenario Analysis

14.8.1 Current Situation (in the 2000s)

A. General Scenario Analysis

The top events were calculated using Saphire®.[728] Table 14.7 shows the characteristic values of the distributions of the top events calculated with inputs obtained from experts using success tree models (See Appendix I for input values). All basic events were assumed to have normal distributions with model parameters, such as means and standard deviations. Thus, the uncertainty of basic event parameters is propagated through the success tree models toward the top events.

[728] The Monte Carlo technique was selected for calculating uncertainty distributions. The number of samples was 1,000 in the calculation.

Table 14.7 Characteristics Values of Probability Distribution of Top Events in the 2000s

Scenarios		Point estimate	mean	5th	median	95th	Standard deviation
Scenario A	Type A (a)	**0.9986**	0.9962	0.9845	0.9989	1	8.646×10^{-3}
	Type B (a)	**1**	1	0.9998	1	1	2.741×10^{-4}
	Type A (b)	**0.9977**	0.9942	0.9741	0.9981	0.9999	1.218x10-2
	Type B (b)	**1**	0.9999	0.9995	1	1	6.210×10^{-4}
Scenario B	Type A/B (a)	**0.9999**	0.9999	0.9997	1	1	1.014×10^{-4}
	Type A/B (b)	**0.9947**	0.9922	0.9786	0.9942	0.9988	6.665×10^{-3}
Scenario C	Type A (a)	**0.9990**	0.9988	0.9977	0.9990	0.9996	6.490×10^{-4}
	Type B (a)	**0.9988**	0.9937	0.9734	0.9983	1	1.467×10^{-2}
	Type A (b)	**0.9949**	0.9926	0.9819	0.9940	0.9981	5.502×10^{-3}
	Type B (b)	**0.9946**	0.9813	0.9300	0.9913	0.9997	2.875×10^{-2}

Notes
[a] Type A countries denote ones with the Additional Protocol and in high level of compliance with the IAEA.
[b] Type B countries denote ones with only Comprehensive Safeguards Agreement and not in high level of compliance with the IAEA.
[c] (a) means that ESWA, LIDAR, and DIAL are not applied.
[d] (b) means that ESWA, LIDAR, and DIAL are assumed to be applied. However, currently, these technologies are not used by the IAEA and require Board of Governors' approval under the Additional Protocol.

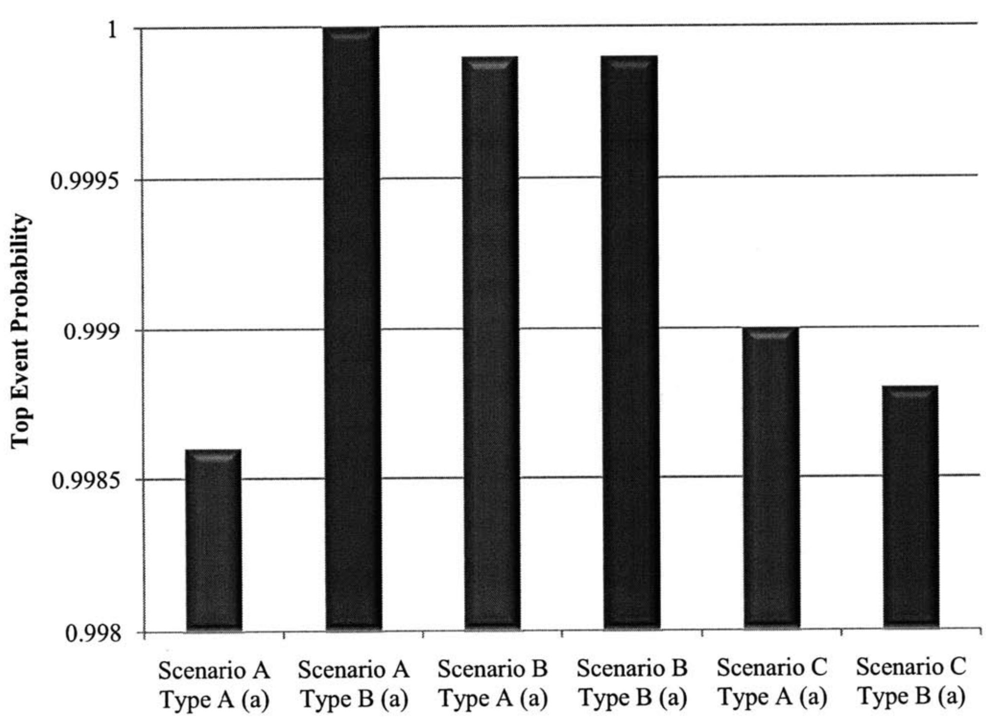


Figure 14.8 Comparison of Top Event Probabilities under Different Scenarios in the 2000s

Figure 14.8 depicts top event probabilities under different scenarios for Type A and Type B countries from the values recorded in Table 14.7. All of these values have very high success probabilities, meaning that once GCEPs are constructed, proliferators' attempt to produce HEU would be highly successful. Under scenario C, Type A countries have the higher top event probability value than Type B countries. This is because Type A countries have higher success probabilities in producing excess LEU, diversion of NUF6 at the declared UCF, and additional conversion of undeclared feed.

On the contrary, under scenario A, Type B countries have the higher top event probability value than Type A countries. This is due to the fact that Type B countries have the higher input values for basic events regarding 'off-design operation modes for producing HEU.' In particular, the unity value of Type B countries implies that the construction of a new GCEP should be prevented. The impact of ESWA/LIDAR/DIAL application is also shown in Table 14.7.

B. Direct Break-out VS Indirect Break-out

As described in Chapter 13, a break-out scenario can be further divided into 'a direct break-out' and 'indirect break-out' scenario, depending on the UER of uranium feed. This section provides a quantitative analysis on those two scenarios. Table 14.8 and Figure 14.9 show the characteristic values of the top event probabilities.

Table 14.8 Characteristics Values of Top Events for Direct- and Indirect Break-out Scenarios in the 2000s

Scenario		Point estimate	mean	5th	median	95th	Standard deviation
Direct	Case I (a)	**0.8735**	0.8996	0.7368	0.8861	0.9615	7.567×10^{-2}
	Case II (a)	**0.9851**	0.9698	0.9031	0.9829	0.9987	3.679x10-2
	Case I (b)	**0.8633**	0.8587	0.6974	0.8807	0.9541	8.008×10^{-2}
	Case II (b)	**0.9788**	0.9582	0.8698	0.9737	0.9978	4.543x10-2
Indirect	Case I (a)	**0.9956**	0.9915	0.9969	0.9962	0.9997	1.507x10-2
	Case II (a)	1	0.9999	0.9995	1	1	4.015×10^{-4}
	Case I (b)	**0.9958**	0.9914	0.9648	0.9966	0.9998	1.735×10^{-2}
	Case II (b)	1	0.9997	0.9985	1	1	1.678×10^{-3}

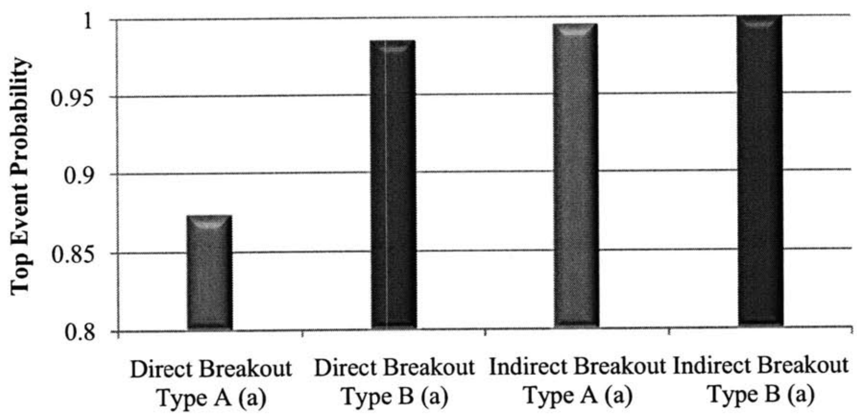


Figure 14.9 Comparison of Top Event Probabilities for Different Break-out Scenarios in the 2000s

Type B countries have the higher top event probabilities in both break-out scenarios. It should be noted that the indirect break-out scenario gives higher success probabilities for a proliferator as they can stockpile LEUF6.

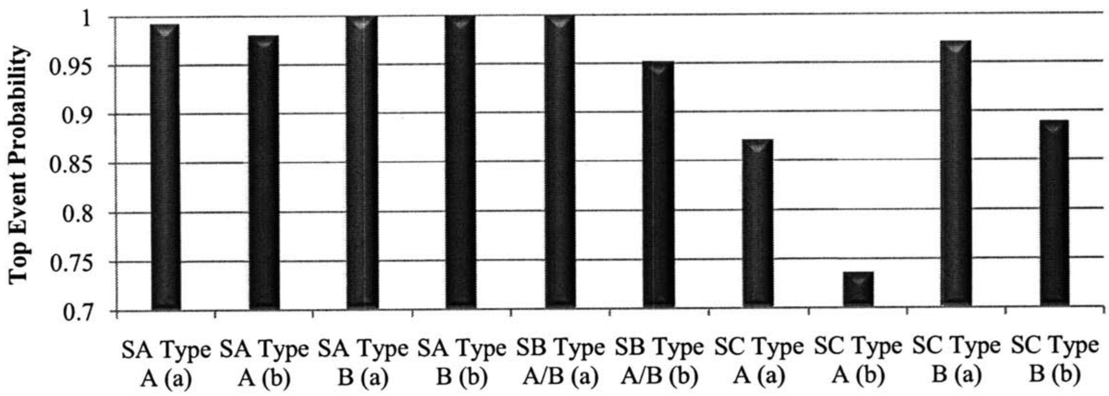
14.8.2 Under Integrated Safeguards System: In the 2010s

A. Generic Scenario Analysis

As reviewed in Chapter 6, the IAEA is currently establishing the Integrated Safeguards System. It is important to note here that the expert opinions contained in this section are based on the assumption that current IAEA's plan is on track. Table 14.9 and Figure 14.10 show the top event probabilities for each scenario. The impact of a generalized use of ESWA/LIDAR/DIAL was also reflected and noted as '(b)' in the Table and Figure.

Table 14.9 Characteristic Values of Probability Distribution of Top Events in the 2010s

Type of Countries	Scenario	Point estimate	mean	5th	median	95th	Standard deviation
Scenario A	Type A (a)	**0.9926**	0.9870	0.9505	0.9940	0.9995	2.075×10^{-2}
	Type B (a)	**1**	0.9991	0.9958	1	1	3.738×10^{-3}
	Type A (b)	**0.9805**	0.9725	0.9176	0.9811	0.9976	2.938×10^{-2}
	Type B (b)	**0.9998**	0.9975	0.9881	0.9998	1	7.816×10^{-3}
Scenario B	Type A/B (a)	**0.9999**	0.9999	0.9997	0.9999	1	1.047×10^{-4}
	Type A/B (b)	**0.9514**	0.9471	0.9004	0.9513	0.9796	2.544×10^{-2}
Scenario C	Type A (a)	**0.8703**	0.8626	0.7198	0.8767	0.9595	7.681×10^{-2}
	Type B (a)	**0.9716**	0.9512	0.8514	0.9667	0.9976	4.924×10^{-4}
	Type A (b)	**0.7343**	0.7242	0.5606	0.7354	0.8752	9.883×10^{-2}
	Type B (b)	**0.8888**	0.8604	0.6756	0.8794	0.9704	9.283×10^{-2}



Note: SA: Scenario A, SB: Scenario B, and SC: Scenario C

Figure 14.10 Comparison of Top Event Probabilities under Different Scenarios in the 2010s

Here, notable difference from the current situation is that the top event probability for Type A countries under Scenario C has the lowest probability among all possible scenarios. In the 2000s, Type A countries under Scenario A has the lowest probability. This is due to the increase in detection probabilities for producing excess LEU for SC Type A(a) and the introduction of ESWA/LIDAR/DIAL for SC Type A (b).

B. Direct Break-out VS Indirect Break-out in the 2010s

Table 14.10 and Figure 14.11 report the top event probabilities under two sub-sets of Scenario A. Type B states still have significantly high success probabilities under the indirect break-out scenario, even though the use of ESWA/LIDAR/DIAL is assumed. This is because a proliferator still has high success probabilities for the basic events such as diversion of nuclear material from declared facilities and excess production of LEU with add-on capacity, without the application of the AP. This emphasizes the importance of prohibiting the new construction of GCEPs in these types of countries.

Table 14.10 Characteristics Values of Top Events for Direct- and Indirect Break-out Scenarios

Scenarios		Point estimate	mean	5th	median	95th	Standard deviation
Direct	Type A (a)	**0.8511**	0.8399	0.6813	0.8565	0.9476	8.783×10^{-2}
	Type B (a)	**0.9652**	0.9377	0.8001	0.9609	0.9977	6.788×10^{-2}
	Type A (b)	**0.8013**	0.7879	0.6021	0.8027	0.9195	1.006×10^{-1}
	Type B (b)	**0.9399**	0.9146	0.7556	0.9377	0.9927	7.543×10^{-2}
Indirect	Type A (a)	**0.9745**	0.9638	0.8815	0.9774	0.9968	3.996×10^{-2}
	Type B (a)	**0.9998**	0.9975	0.9869	0.9998	1	6.960×10^{-3}
	Type A (b)	**0.9325**	0.9224	0.8117	0.9368	0.9864	5.622×10^{-2}
	Type B (b)	**0.9988**	0.9923	0.9647	0.9985	1	1.713×10^{-2}

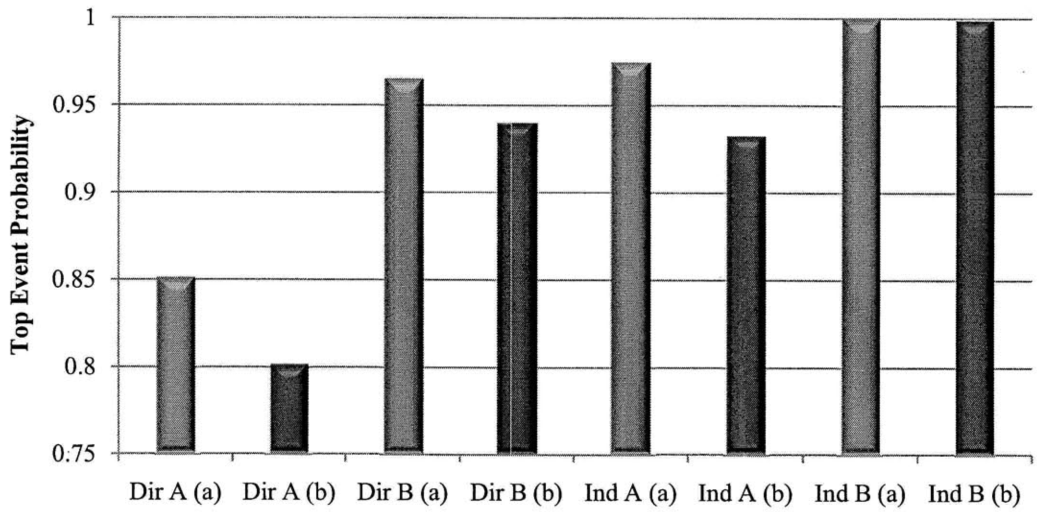
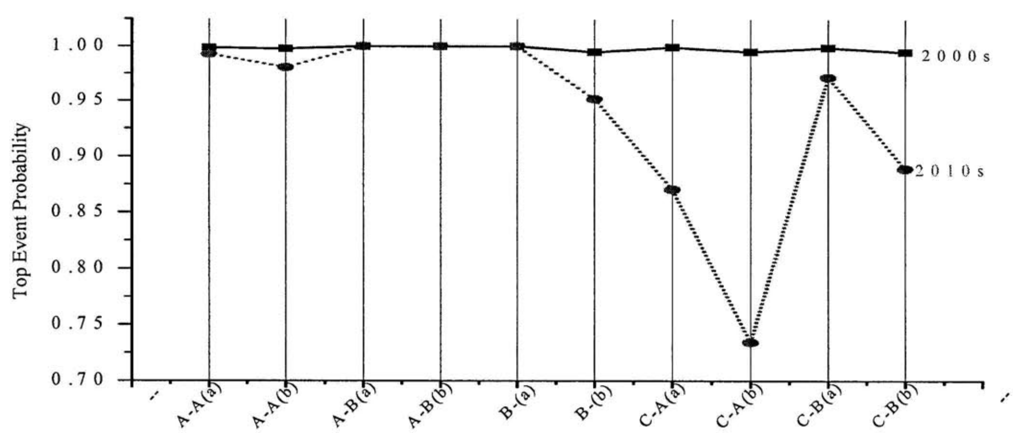


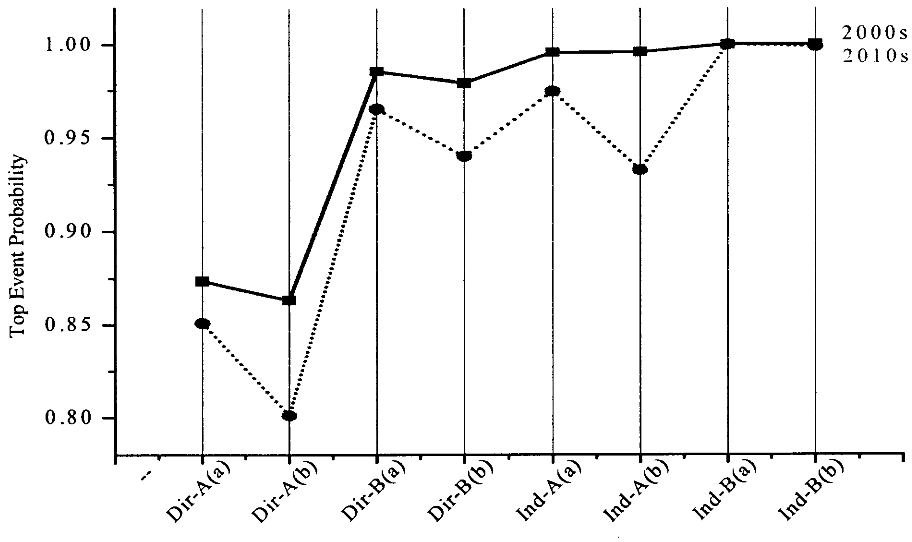
Figure 14.11 Comparison of Top Event Probabilities for Different Break-out Scenarios in the 2010s

14.8.3 Time Trend

Figure 14.12 shows the changes in top event probabilities as the IAEA's Integrated Safeguards System (ISS) gets to the matured stage. In Figure 14.12 (a), the top event probabilities under Scenario C are expected to significantly decrease compared to the current IAEA safeguards system. Notably, as ESWA/LIDAR/DIAL is introduced, the top event probability for Type B countries under Scenario C is expected to decrease. The IAEA's capabilities in dealing with Scenario C are expected to improve significantly. On the contrary, the top event probabilities for Type B countries under Scenario A and Scenario B (a) do not decrease, meaning that the establishment of ISS is not enough to safeguard declared GCEPs in Type B countries. This implies that the IAEA should take significant measures to deal with this case.



(a) Scenarios A, B, and C



(b) Direct VS Indirect Scenarios

Figure 14.12 Changes in Top Event Probabilities from 2000s to 2010s

Figure 14.12 (b) shows the analysis on Type B countries under two sub-sets of Scenario A: direct and indirect. This figure clearly shows the impact of establishing the ISS except for the case of Type B countries under the indirect break-out scenario.

14.9 Uncertainty Analysis

This section reviews uncertainty propagation through different epistemic uncertainty distributions of basic events. The model employed for this work has a number of uncertainties. First, the integrated methodology was applied assuming a typical nuclear fuel cycle in order to take advantage of study results available in literature. Thus, the results are likely to vary in cases where state(s) in question do not possess typical nuclear fuel cycle(s). Second, input data for basic events, evaluated by experts, are also subject to uncertainties associated with the state-of-knowledge.

In the present study, uncertainty analysis was completed for two categories of basic events under scenario B: Illicit acquisition of nuclear material-associated and ESWA/LIDAR/DIAL detection-associated events. These two categories were chosen because these are considered to have the highest levels of uncertainty among all basic events due to the unavailability of relevant information or research. Table 14.11 lists the selected basic events and their input values. Changed input values were prepared in order to perform uncertainty analysis by multiplying the original standard deviation values by a factor of 2 for a parametric sensitivity study.

Table 14.11 Changes of Input Values for Uncertainty Analysis

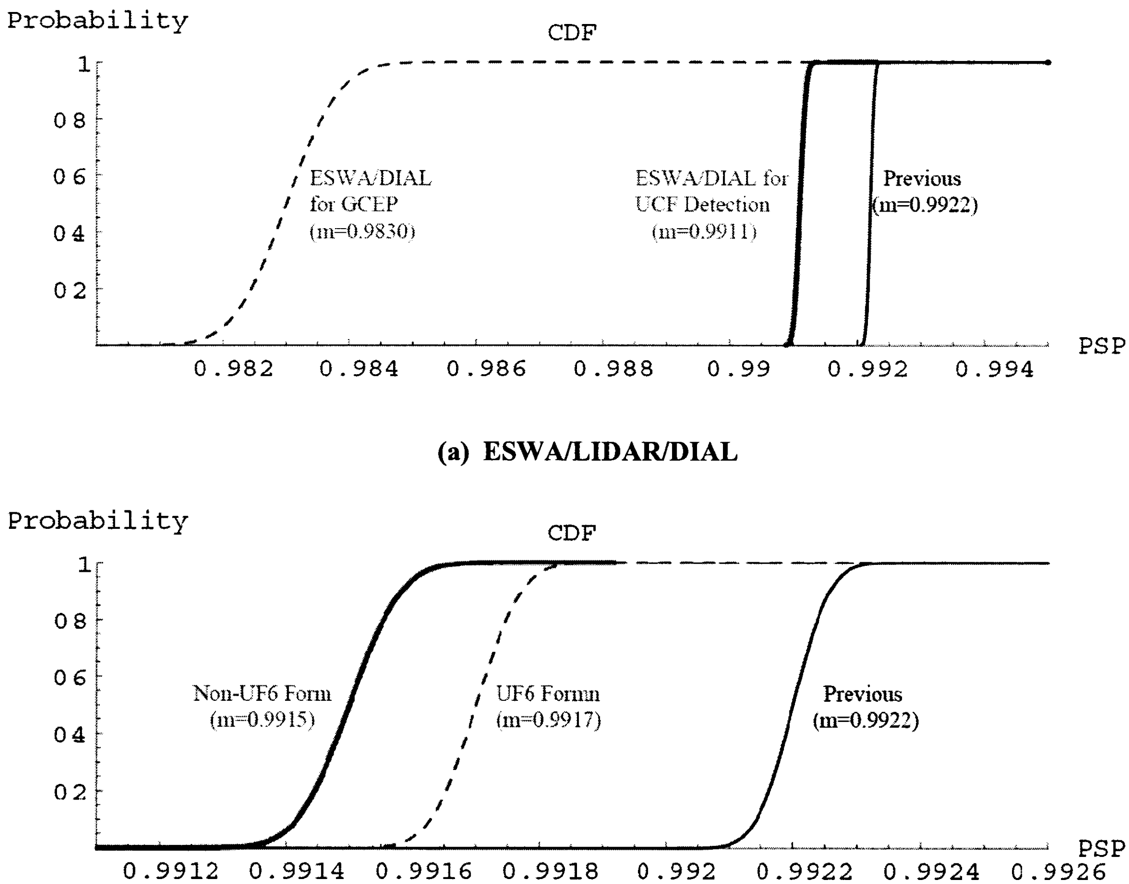
Basic Events Description	Original inputs		Changed inputs	
	mean	Standard deviation	mean	Standard deviation [a]
Clandestine GCEP operation is not detected by ESWA/DIAL at short distances.	0.88	0.088	0.88	0.176
Clandestine UCF operation is not detected by ESWA/LIDAR at short distances.	0.75	0.075	0.75	0.15
Illicit acquisition of NU (Non-UF6) is not detected.	0.825	0.0825	0.825	0.165
Illicit acquisition of NUF6 is not detected.	0.75	0.075	0.75	0.15

Note: [a] The standard deviation of original inputs was multiplied by a factor of 2

The changed probability distributions of the top event generated through varying standard deviation values for the selected basic events are shown in Table 14.12 and Figure 14.13. This table shows that uncertainty distributions of the selected basic events are propagated to the top event probability through the structure of the success trees.

Table 14.12 Results of Probability Distributions of Top Events from Changed Different Uncertainty Distributions of Basic Events

Inputs	Point estimate	mean	5th percentile	median	95th percentile	Standard deviation
Previous	0.9947	0.9922	0.9786	0.9942	0.9988	6.665×10^{-3}
ESWA/DIAL for GCEP	0.9947	0.9830	0.9404	0.9917	0.9987	2.569×10^{-2}
ESWA/LIDAR for UCF Detection	0.9947	0.9911	0.9755	0.9936	0.9989	8.368×10^{-3}
Non-UF6 form	0.9947	0.9917	0.9768	0.9938	0.9988	7.467×10^{-3}
UF6 Form	0.9947	0.9921	0.9781	0.9943	0.9990	8.096×10^{-3}



(a) ESWA/LIDAR/DIAL

(b) Illicit Acquisition of Nuclear Material

Figure 14.13 Changes of Cumulative Distribution Functions through Changes in Standard Deviation Values for Basic Events

14.10 Sensitivity Analysis

14.10.1 Sensitivity of the Top Event Probability to Individual Input Values

A sensitivity analysis was completed to further explore the effect of varying an input value for a selected basic event toward the top event probability. Sensitivity analyses are useful for identifying the key variables that may have the most significant consequences on the end state.

In order to perform a sensitivity analysis in the present study, an input value for individual basic events were varied in turn while the other variables were kept constant. Table 14.13 lists the values of input variables that were used to investigate the sensitivity of the top event to each basic event. Under scenario C for Case III, Type A is stated with the assumed application of ESWA/LIDAR/DIAL. The input values for selected basic events were multiplied by a factor of 0.9, 0.6, and 0.3, respectively, in order to determine whether an increase in safeguarders' capabilities have an impact on success probabilities of proliferators. Basic events related to the illicit acquisition of nuclear material and ESWA/LIDAR/DIAL were analyzed in the uncertainty analysis.

Table 14.13 Changed Input Values and Results of Top Event Probabilities for Case III under Scenario C

Basic event		Mean Value of Basic Event Probability			
		Base case	Case I (Base x 0.9)	Case II (Base x 0.6)	Case III (Base x0.3)
A	NU feed provision through illicit acquisition is not detected.	0.825	0.7425	0.495	0.2475
	Top event probabilities for each case	0.9947	0.9940	0.9921	0.9902
B	LEUF6 feed provision through illicit acquisition is not detected.	0.75	0.675	0.45	0.225
	Top event probabilities for each case	0.9947	0.9936	0.9906	0.9875
C	Clandestine UCF operation is not detected by ESWA/LIDAR at short distances.	0.75	0.675	0.45	0.225
	Top event probabilities for each case	0.9947	0.9917	0.9753	0.9422
D	Clandestine GCEP operation is not detected by ESWA/DIAL at short distances.	0.88	0.792	0.528	0.264
	Top event probabilities for each case	0.9947	0.978	0.8889	0.6245

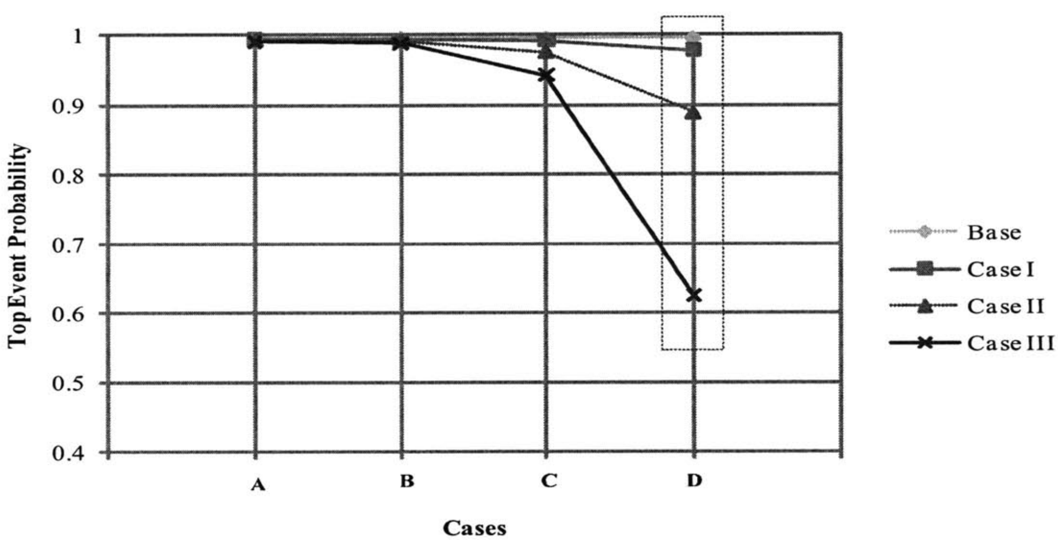


Figure 14.14 Sensitivity of Proliferator Success Probability (PSP) through Sensitivity Analysis

Figure 14.14 illustrates the results of sensitivity analysis with varying input values for each basic event. This figure shows that basic events associated with the capabilities of ESWA/LIDAR/DIAL generated the largest variation in the top event probability value. This result implies that more investment in developing ESWA/LIDAR/DIAL technology may produce higher returns than other options.

14.10.2 Sensitivity of Top Event Probabilities to Different Experts

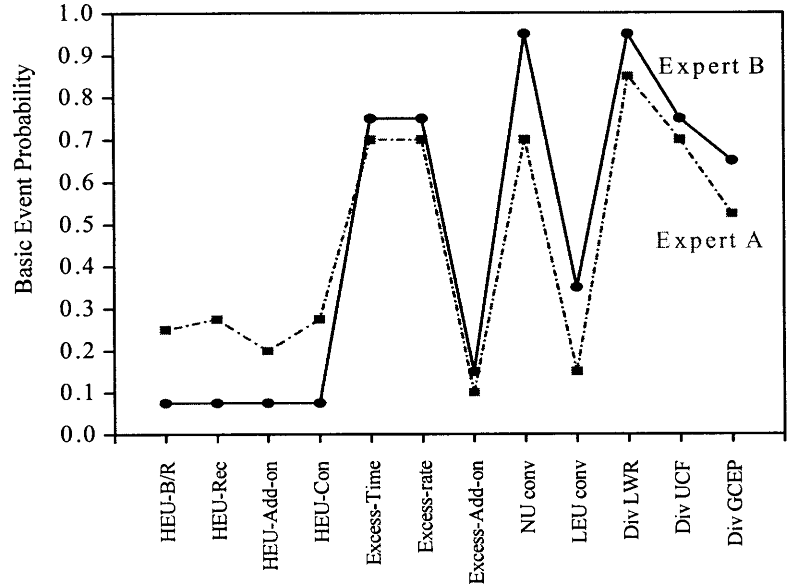
In the present study, multiple experts were available for basic events related to off-design operation of declared GCEPs for producing HEU, conversion of undeclared nuclear material at declared UCFs, and diversion of nuclear material from declared nuclear facilities. Thus, the sensitivity of top event probabilities to experts were investigated only using these two categories of basic events, whereas other categories of basic events were assumed to remain unchanged. Table 14.14 and Figure 14.15 show the different input values provided by two different experts concerning two categories of basic events.

Table 14.14 Different Input Values of Experts A and B Used for Sensitivity Analysis

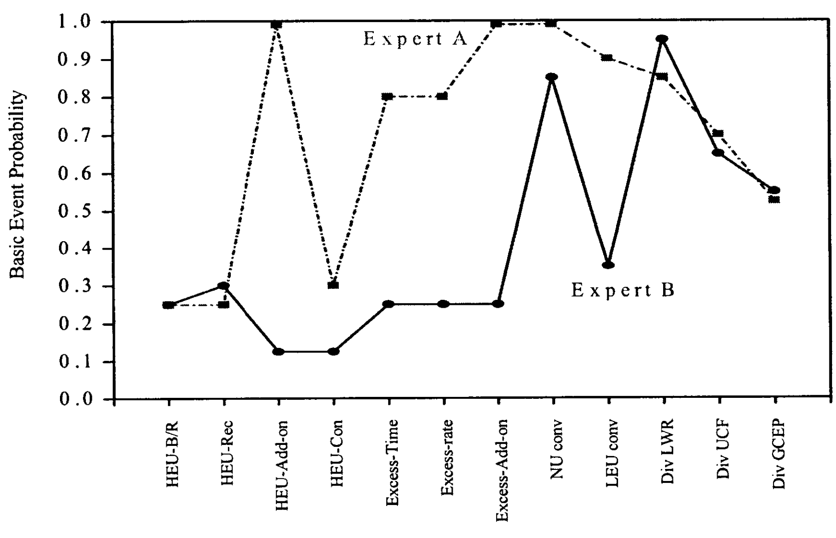
Category	Proliferation activities for BEs	Type A		Type B	
		Expert A	Expert B	Expert A	Expert B
		Mean	Mean	Mean	Mean
Off-design operation for HEU production	Batch recycling	0.25	0.075	0.25	0.25
	Reconfiguration	0.275	0.075	0.25	0.3
	Add-on operation	0.2	0.075	0.99	0.125
	Cascade connection	0.275	0.075	0.3	0.125
Excess LEU production	Additional time	0.7	0.75	0.8	0.25
	Increase product rate	0.7	0.75	0.8	0.25
	Add-on operation	0.1	0.15	0.99	0.25
Declared UCF operation with undeclared feed	NU Conversion	0.7	0.95	0.99	0.85
	LEU Conversion	0.15	0.35	0.9	0.35
Declared material diversion from declared nuclear facilities	LWR	0.85	0.95	0.85	0.95
	UCF	0.7	0.75	0.7	0.65
	GCEP	0.525	0.65	0.525	0.55
	FFP	N/A	0.7	N/A	0.7

Note: Only expert B provided evaluation for Fuel Fabrication Plant (FFP).

The input values obtained from two experts are in good agreement for Type A countries, whereas there are big differences for Type B countries. In addition, Expert B provided, in general, higher values than Expert A for Type A countries with the exception of excess LEU production. On the contrary, Expert A provided higher values for Type B countries except for HEU production in reconfiguration mode and nuclear material diversion from LWRs.



(a) Type A Countries



(b) Type B Countries

Figure 14.15 Graphical Comparison of Different Experts Opinion

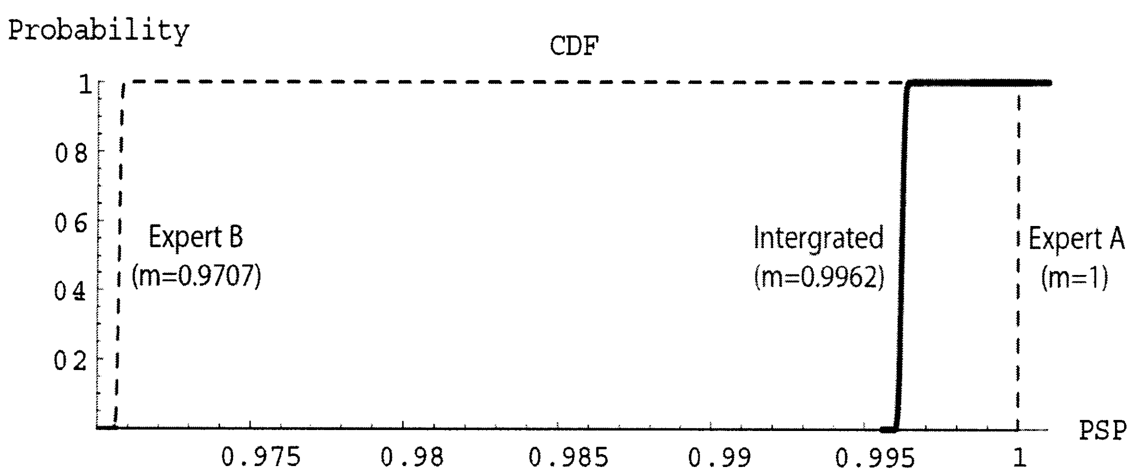
The top event probabilities were then calculated using two input values provided by different experts, and the characteristic values of top event probability distributions are tabulated in Table 14.15.

Table 14.15 Comparison of the Probability Distributions of the Top Event Concerning Different Experts' Inputs without ESWA/LIDAR/DIAL Application

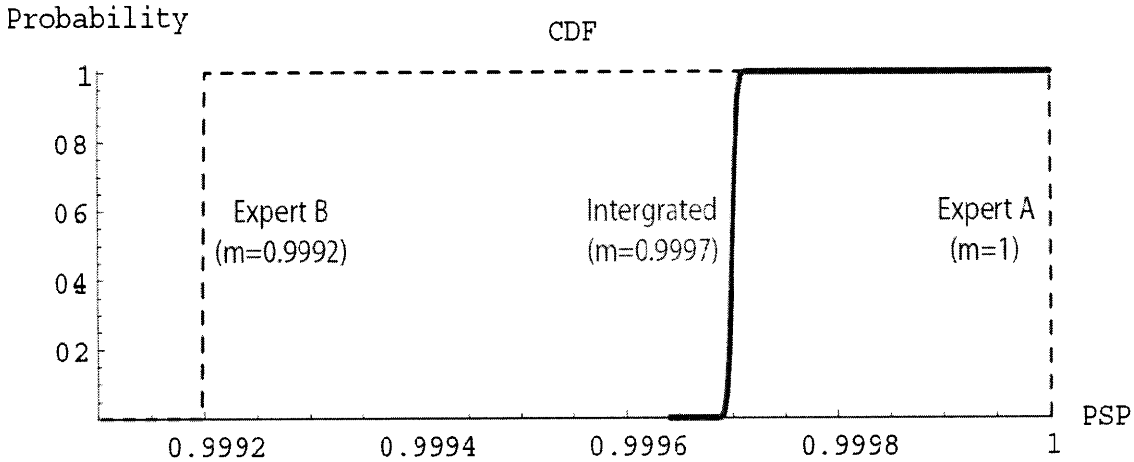
Case		Category	Point	mean	5^{th}	median	95^{th}	Standard deviation
Scenario A	Type A	Expert A	1	1	1	1	1	1.801×10^{-5}
		Expert B	0.9729	0.9707	0.9576	0.9715	0.9805	7.202×10^{-3}
		Integrated	0.9986	0.9962	0.9845	0.9989	1	8.646×10^{-3}
	Type B	Expert A	1	1	1	1	1	0
		Expert B	0.9993	0.9992	0.9985	0.9993	0.9997	3.976×10^{-4}
		Integrated	1	0.9997	0.9993	1	1	1.941×10^{-3}
Scenario C	Type A	Expert A	0.9984	0.9980	0.9950	0.9983	0.9996	1.468×10^{-3}
		Expert B	0.9998	0.9996	0.9987	0.9997	1	4.403×10^{-4}
		Integrated	0.999	0.9988	0.9977	0.999	0.9996	6.490×10^{-4}
	Type B	Expert A	1	1	1	1	1	1.4×10^{-5}
		Expert B	0.9573	0.9555	0.9353	0.9569	0.9716	1.111×10^{-2}
		Integrated	0.9988	0.9937	0.9734	0.9983	1	1.467×10^{-2}

Note: The integrated values are from Table 14.7

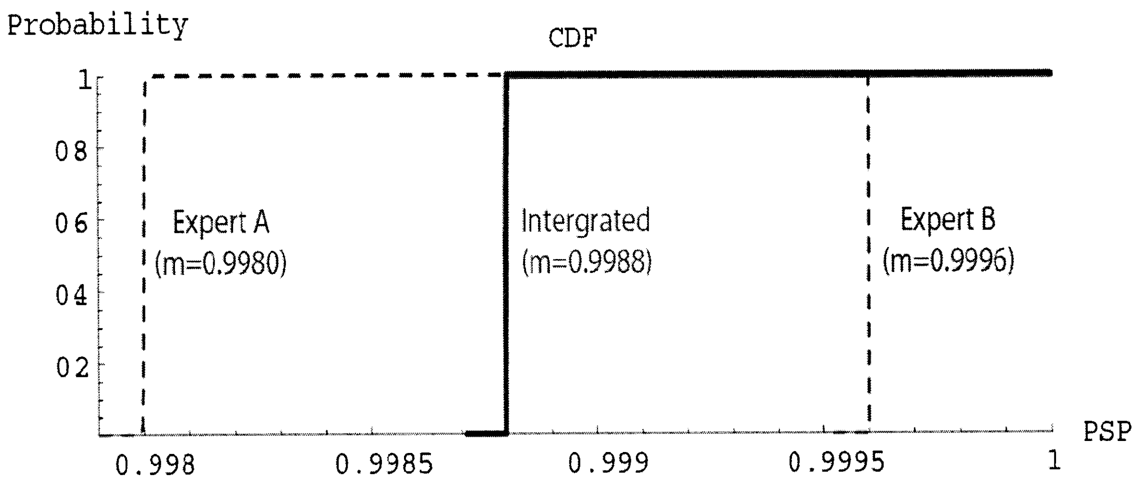
Figure 14.16 illustrates the Cumulative Distribution Functions (CDFs) of the top event probabilities for each case.



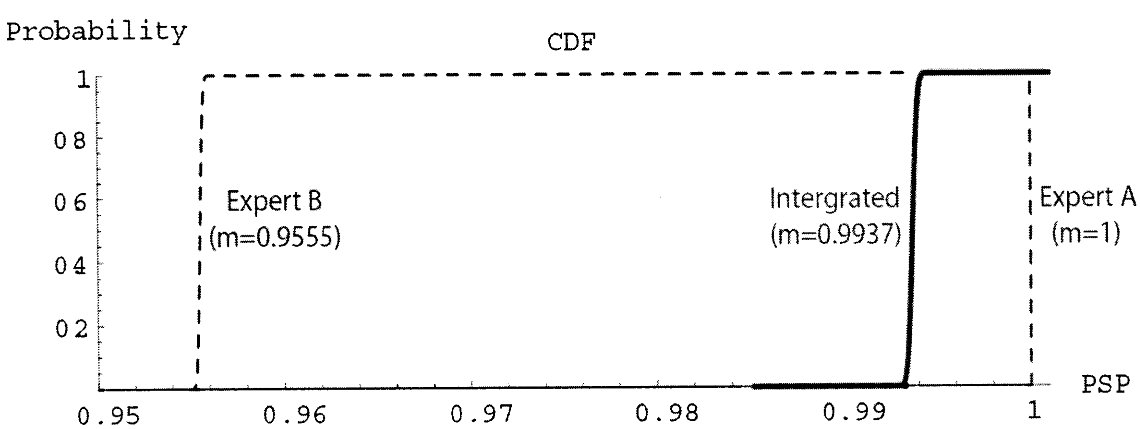
(a) Type A states under scenario A



(b) Type A States under Scenario C



(c) Type B States under Scenario A



(d) Type B States under Scenario C

Figure 14.16 Comparison of the Distributions of the Top Event Probability Based on Different Expert Inputs

14.11. Importance Analysis

14.11.1 Rankings of Minimal Path Sets (MPSs)

An importance analysis was completed to identify important sets of events that lead to the end state of a proliferator being successful (i.e., HEU production without detection), which are typically called Minimal Path Sets (MPSs) in success trees. For each scenario, importance analysis enables the identification of the most favorable pathways toward the proliferators' success. A total of 88, 6, and 13 MPSs were generated under scenarios A, B, and C, respectively. In this study, Scenario C was chosen for the analysis because this can be the case of possible proliferation states including Iran.

A. MPSs for Type A Countries under Scenario C

The MPSs for Type A countries under Scenario C are described in Table 14.16 according to their rankings.

Table 14.16 Description of MPSs for Type A Countries under Scenario C

MPS(i)	Material acquisition (form)	Uranium conversion	Excess LEU production	Clandestine GCEP Detection
MPS1	NU (C1)	Clandestine UCF (C8, C9)	Increased product rate (C13)	C14-C17
MPS2	NU (C1)	Clandestine UCF (C8, C9)	Additional time (C12)	C14-C17
MPS 3	NUF6 (C2)	-	Increased product rate (C13)	C14-C17
MPS 4	NUF6 (C2)	-	Additional time (C12)	C14-C17
MPS 5	LEUF6 diversion from GCEP (C7)	-	-	C14-C17
MPS 6	NUF6 diversion from UCF (C5)	-	Increased product rate (C13)	C14-C17
MPS 7	NUF6 diversion from UCF (C5)		Additional time (C12)	C14-C17
MPS 8	NU (C1)	Declared UCF (C10)	Additional time (C12)	C14-C17
MPS 9	NU (C1)	Declared UCF (C10)	Increase product rate (C13)	C14-C17
MPS 10	NU (C1)	Clandestine (C8, C9)	Add-on (C11)	C14-C17
MPS 11	NUF6 (C2)	-	Add-on (C11)	C14-C17
MPS 12	NUF6 diversion from UCF (C5)	-	Add-on (C11)	C14-C17
MPS 13	NU (C1)	Declared UCF (C10)	Add-on (C11)	C14-C17

As shown in Table 14.17, the rankings of each MPS are affected by two factors: material acquisition paths and the operation mode for producing excess LEU with detection means for the clandestine GCEP being included in MPSs. The probabilities and rankings of MPSs calculated from integrated inputs, inputs from expert A, and inputs from expert B are shown in the Table.

Table 14.17 Ranking of MPS in Different Experts for Type A Countries under Scenario C

Rankings from integrated inputs	Integrated Pr (MPSi)	Rankings from Expert A	Expert A Pr(MPSi)	Rankings from Expert B	Expert B Pr(MPSi)
MPS 1	0.587	MPS 1	0.567	MPS 5	0.637
MPS 2	0.587	MPS 2	0.567	MPS 1	0.607
MPS 3	0.534	MPS 3	0.515	MPS 2	0.607
MPS 4	0.534	MPS 4	0.515	MPS 8	0.576
MPS 5	0.516	MPS 5	0.515	MPS 9	0.576
MPS 6	0.516	MPS 6	0.481	MPS 3	0.552
MPS 7	0.503	MPS 7	0.481	MPS 4	0.552
MPS 8	0.426	MPS 8	0.397	MPS 6	0.552
MPS 9	0.426	MPS 9	0.397	MPS 7	0.552
MPS 10	0.101	MPS 10	0.081	MPS 10	0.12
MPS 11	0.092	MPS 11	0.074	MPS 13	0.115
MPS 12	0.089	MPS 12	0.069	MPS 11	0.11
MPS 13	0.073	MPS 13	0.057	MPS 12	0.11

Figure 14.17 illustrates comparison of probabilities and rankings of the MPSs for proliferators' success. The result shows that important rankings of MPSs vary over different expert opinions. Expert A inputs generated the result that MPS 1 is the most significant MPS, where as Expert B inputs led to the result that MPS 5 is the most important one.

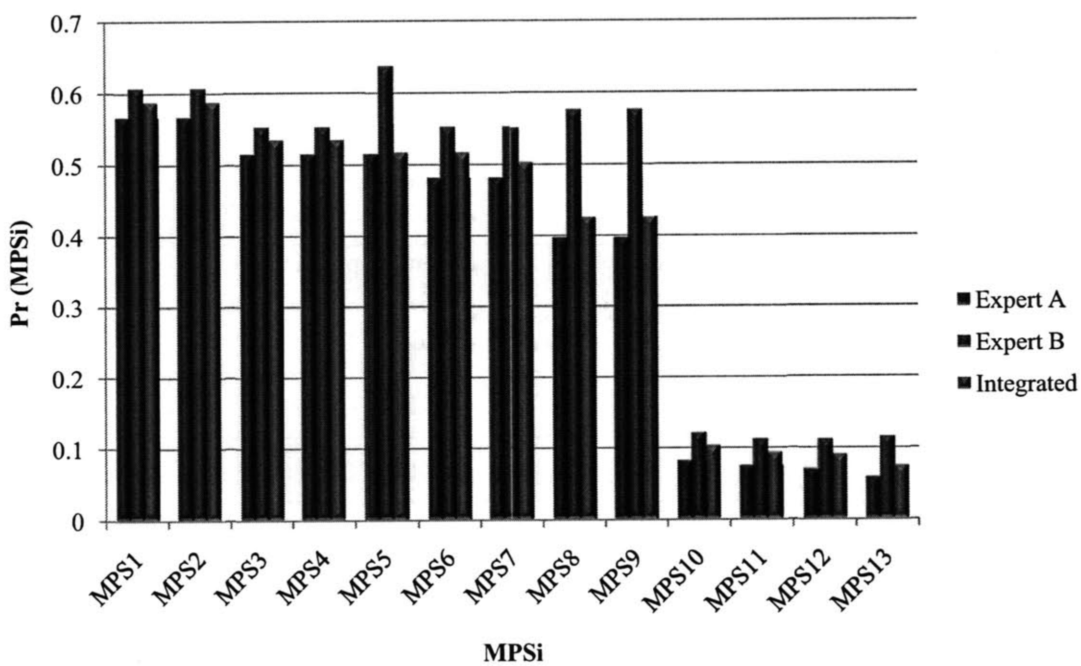


Figure 14.17 Comparison of the Proliferator Success Probabilities for Different MPSs for Type A Countries under Scenario C

B. MPSs for Type B Countries under Scenario C

The identified MPSs for Type B countries under Scenario C are listed in Table 14.18. Under this scenario, MPS1, producing HEU using directly diverted LEUF6 from a declared GCEP, is the most significant MPS.

Table 14.18 Description of MPSs for Type B Countries under Scenario C

MPS(i)	Material acquisition	Uranium conversion	Excess LEU production	Clandestine GCEP detection
MPS1	LEUF6 diversion from GCEP (C7)	-	-	C14-C17
MPS2	NU (C1)	Clandestine (C8, C9)	Add-on (C11)	C14-C17
MPS 3	NU (C1)	Clandestine (C8, C9)	Additional time (C12)	C14-C17
MPS 4	NU (C1)	Clandestine (C8, C9)	Increase product rate (C13)	C14-C17
MPS 5	NUF6 (C2)	-	Add-on (C11)	C14-C17
MPS 6	NUF6 (C2)	-	Increased product rate (C13)	C14-C17
MPS 7	NUF6 (C2)	-	Additional time (C12)	C14-C17
MPS 8	NUF6 diversion from UCF (C5)		Add-on (C11)	C14-C17
MPS 9	NU (C1)	Declared UCF (C10)	Add-on (C11)	C14-C17
MPS 10	NUF6 diversion from UCF (C5)		Increased product rate (C13)	C14-C17
MPS 11	NUF6 diversion from UCF (C5)		Additional time (C12)	C14-C17
MPS 12	NU (C1)	Declared UCF (C10)	Increased product rate (C13)	C14-C17
MPS 13	NU (C1)	Declared UCF (C10)	Additional time (C12)	C14-C17

Table 14.19 and Figure 14.18 show the changes in the rankings of MPSs according to Expert A, Expert B, and integrated input values. Expert A notes that MPSs involving illicit acquisition of NU are the most threatening for proliferation opportunities. On the contrary, Expert B sees that MPS1, LEU diversion from a declared GCEP is the most threatening.

Table 14.19 MPS Rankings of Different Experts for Type B Countries under Scenario C

Rankings from integrated inputs	Integrated Pr (MPSi)	Rankings from Expert A	Expert A Pr(MPSi)	Rankings from Expert B	Expert B Pr(MPSi)
MPS 1	0.576	**MPS 2**	0.801	**MPS 1**	0.539
MPS 2	0.465	MPS 9	0.793	MPS 2	0.202
MPS 3	0.425	MPS 5	0.728	MPS 3	0.202
MPS 4	0.425	MPS 8	0.679	MPS 4	0.202
MPS 5	0.423	MPS 3	0.647	MPS 5	0.184
MPS 6	0.386	MPS 4	0.647	MPS 6	0.184
MPS 7	0.386	MPS 12	0.64	MPS 7	0.184
MPS 8	0.380	MPS 13	0.64	MPS 9	0.172
MPS 9	0.360	MPS 6	0.588	MPS 12	0.172
MPS 10	0.347	MPS 7	0.588	MPS 13	0.172
MPS 11	0.347	MPS 10	0.549	MPS 8	0.159
MPS 12	0.329	MPS 11	0.549	MPS 10	0.159
MPS 13	0.329	MPS 1	0.515	MPS 11	0.159

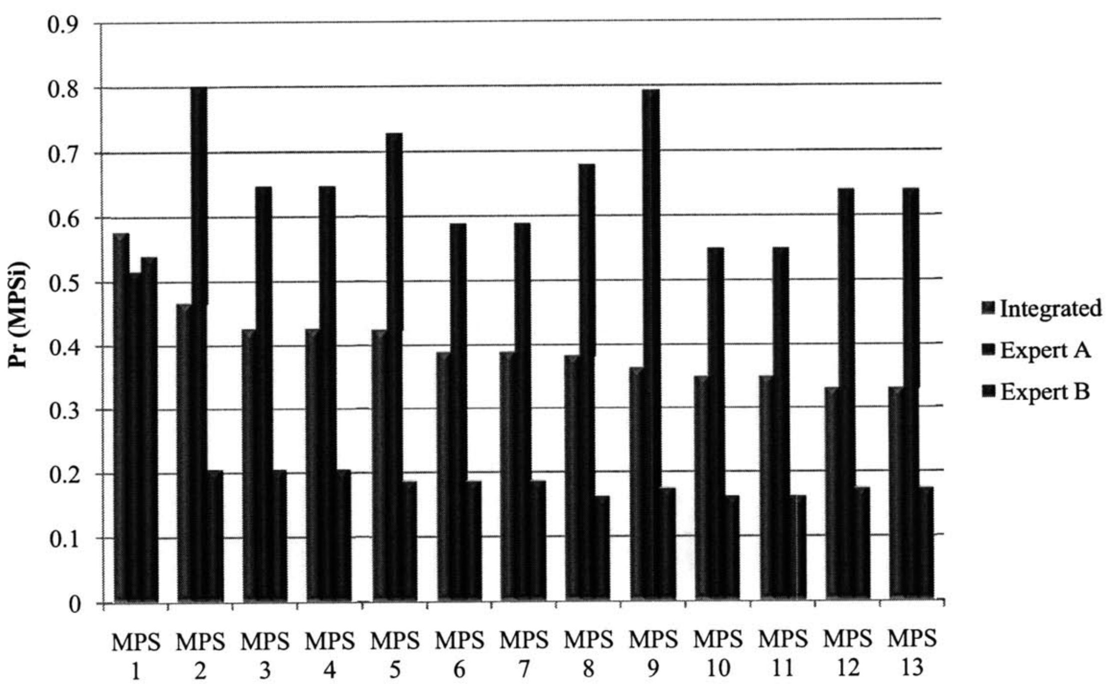


Figure 14.18 Comparison of the Proliferator Success Probabilities for Different MPSs for Type B Countries under Scenario C

14.11.2 Importance Measure Analysis

A. Fussell-Vesely (F-V) Importance for Type B States under Scenario C

F-V importance measure is used in order to evaluate the significance of each basic event under the assumption that the event always fails in success trees. The F-V of a basic event is the fraction of the normal top event probability that would be reduced if the event has the probability value of 'zero' (i.e., a basic event-related proliferation activity is always detected by safeguarders.) The larger the F-V, the greater the importance of the basic event. This means that one can prioritize resources based on the values of F-V importance. However, large F-Vs mean that the events are relatively unreliable, or the event is relatively important. If F-V (BEi) has 0.3, then if Pr (BEi) =0, the top event probability would decrease by 30%. Table 14.20 shows the F-V values for Type B states under scenario C.

Table 14.20 Fussell-Vesely Importance for Type B Countries under Scenario C

Basic event description	No. of occurrence	Pr (BEi)	FV importance
Clandestine GCEP operation is not detected by ESWA/DIAL at short distances.	13	1	1
Clandestine GCEP operation is not detected by ESWA/DIAL at long distances.	13	1	1
Clandestine GCEP operation is not detected by military satellite imagery.	13	1	1
Clandestine GCEP operation is not detected by commercial satellite imagery.	13	1	1
NU provision through illicit acquisition is not detected.	6	0.825	2.32×10^{-2}
Excess LEU production with add-on modular cascades is not detected.	4	0.575	8.93×10^{-3}
Excess LEU production at additional time is not detected.	4	0.525	6.80×10^{-3}
Excess LEU production at an increased production rate is not detected.	4	0.525	6.80×10^{-3}
Clandestine UCF operation is not detected by ESWA/LIDAR at short distances.	3	1	5.78×10^{-3}
Clandestine UCF operation is not detected by ESWA/LIDAR at long distances.	3	1	5.78×10^{-3}
NUF6 provision through illicit acquisition is not detected.	3	0.75	4.48×10^{-3}
NUF6 diversion from UCF is not detected.	3	0.675	3.47×10^{-3}
Undeclared NU conversion at declared UCF is not detected.	3	0.775	3.08×10^{-3}
LEU6 diversion within the declared GCEP is not detected.	1	0.5875	1.69×10^{-3}

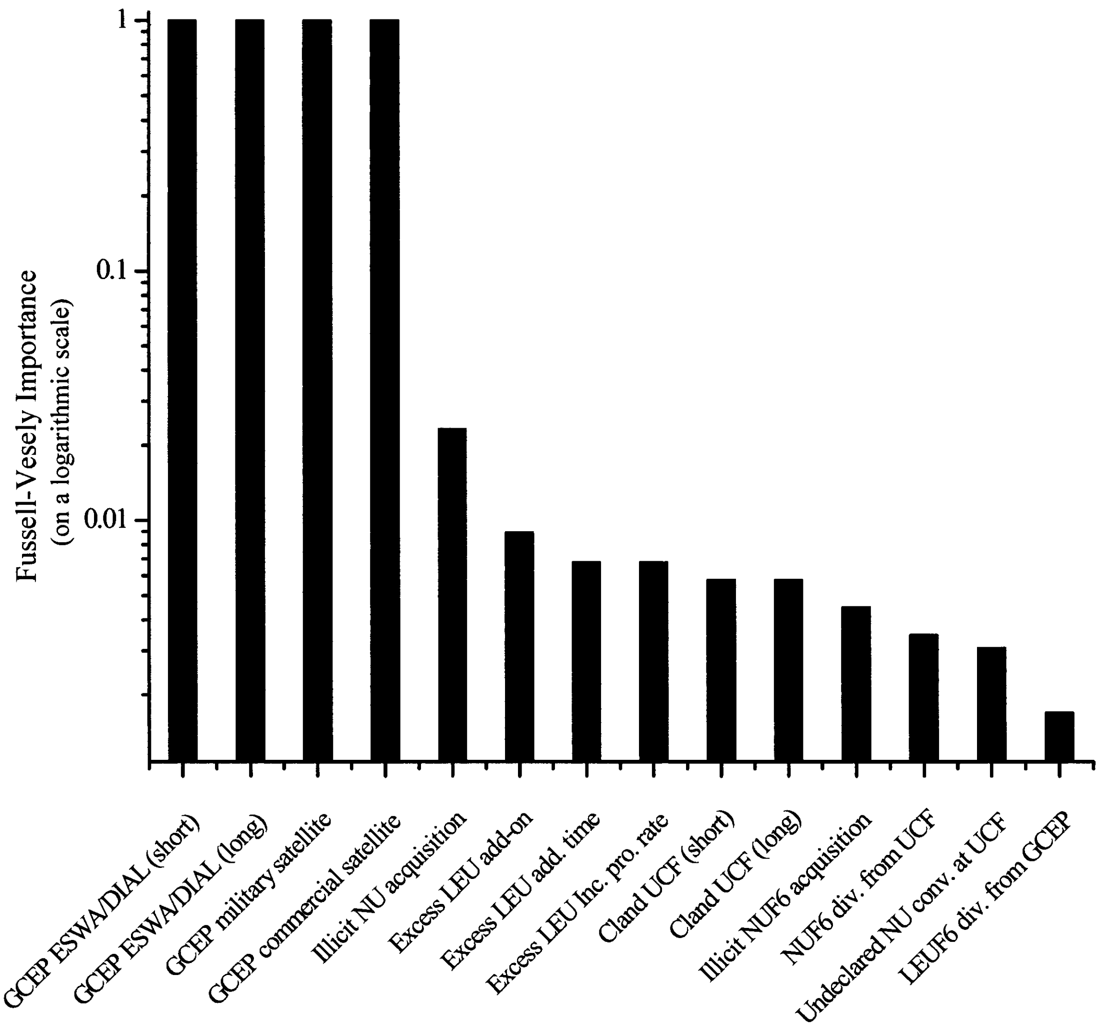


Figure 14.19 Fussell-Vesely Importance for Type B Countries under Scenario C

Figure 14.19 is a graphical representation of values in Table 14.18. The four basic events related to the remote detection technologies have the value of the unity for F-V importance. Except for those four events, it can be said that the most important factor is the control of non-UF_6 form of NU for Type B countries under Scenario C.

B. Sensitivity of Fussell-Vesely Importance to Different Experts

Table 14.21 shows the sensitivity of F-V importance measure to different experts. There exists several orders of magnitude difference in F-V importance values between F-V importance values between Expert A and Expert B except for the detection of clandestine GCEP-related basic events. Again, apart from basic events related to the detection of clandestine GCEPs, the relative importance of controlling NU illicit transfer is recognized.

Table 14.21 Fussell-Vesely Importance of Different Experts for Type B Countries under Scenario C

Basic event description	Expert A	Expert B
	F-V	F-V
Clandestine GCEP operation is not detected by ESWA/DIAL at short distances.	1	1
Clandestine GCEP operation is not detected by ESWA/DIAL at long distances.	1	1
Clandestine GCEP operation is not detected by military satellite imagery.	1	1
Clandestine GCEP operation is not detected by commercial satellite imagery.	1	1
NU provision through illicit acquisition is not detected.	$1.463x10^{-3}$	$1.107x10^{-1}$
Excess LEU production with add-on modular cascades is not detected.	$2.694x10^{-4}$	$5.413x10^{-2}$
Excess LEU production at additional time is not detected.	$4.045x10^{-5}$	$5.413x10^{-2}$
Excess LEU production at an increased production rate is not detected.	$4.045x10^{-5}$	$5.413x10^{-2}$
Clandestine UCF operation is not detected at short distances.	$3.832x10^{-5}$	$4.351x10^{-2}$
Clandestine UCF operation is not detected at long distances.	$3.832x10^{-5}$	$4.351x10^{-2}$
Undeclared NU conversion at declared UCF is not detected.	$3.546x10^{-5}$	$3.415x10^{-2}$
NUF6 provision through illicit acquisition is not detected.	$2.018x10^{-5}$	$3.767x10^{-2}$
NUF6 diversion from UCF is not detected.	$1.40x10^{-5}$	$3.415x10^{-2}$
LEU6 diversion within the declared GCEP is not detected.	$1.036x10^{-6}$	$5.251x10^{-2}$

C. Under Indirect Break-out Scenario

Table 14.22 and Figure 14.20 show the difference in F-V importance values for Type A and Type B countries under the indirect break-out scenario. This result shows the importance of the detection of clandestine UCF operation and the control of Non-UF6 NU international transfer for both Type A and Type B countries. It should be noted that in the case of Type B countries, the basic event related to the detection of HEU production with add-on capacity has the highest F-V importance value. This implies that complementary access would be the most crucial to reducing the proliferator's success probability for producing HEU.

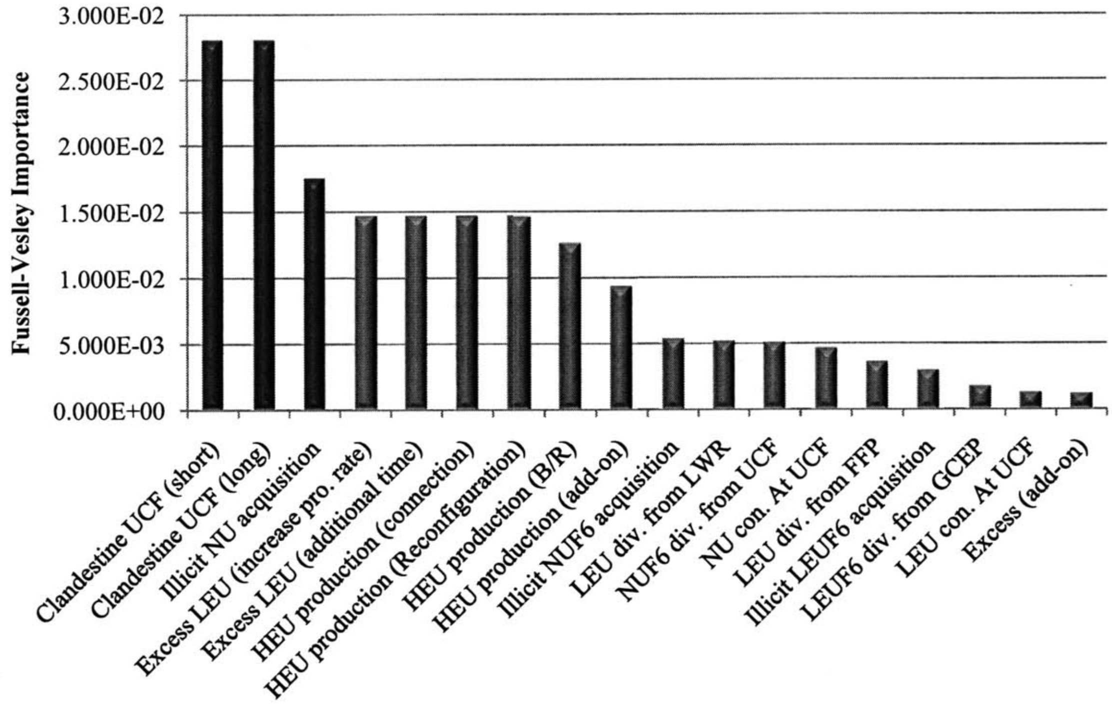
Table 14.22 Fussell-Vesely Importance under Indirect Break-out Scenario

For Type A countries

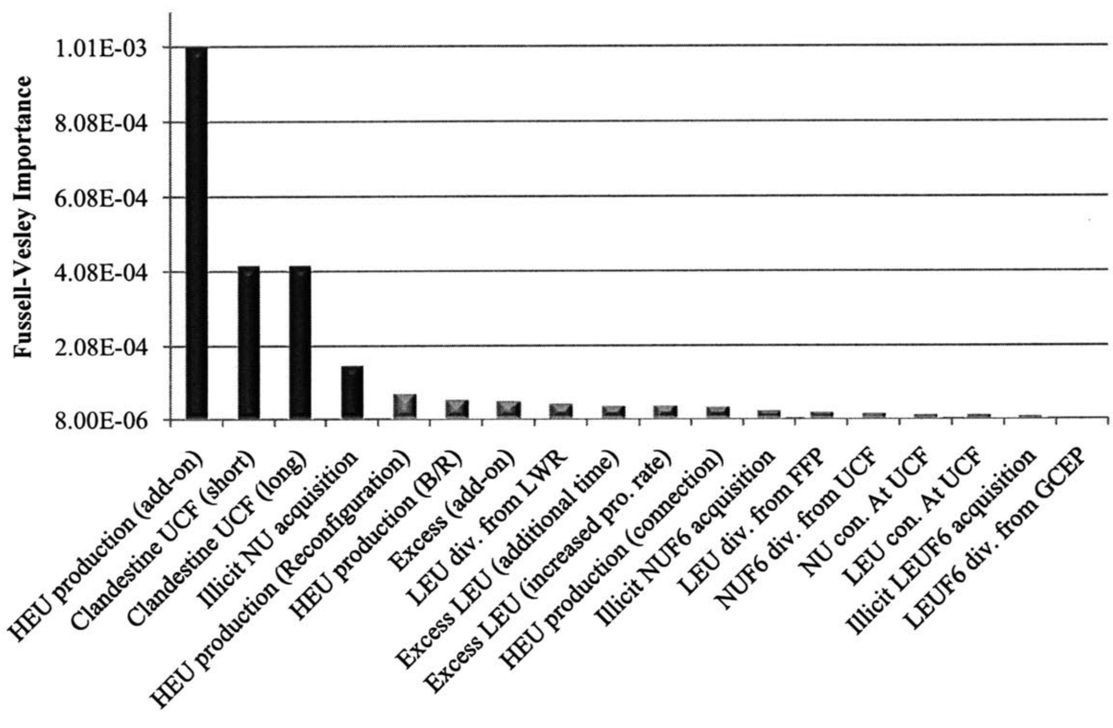
Event Description	No of occurrence	Pr (BEi)	F-V importance
Clandestine UCF operation is not detected by ESWA/LIDAR at short distances.	20	1	2.805×10^{-2}
Clandestine UCF operation is not detected by ESWA/LIDAR at long distances.	20	1	2.805×10^{-2}
NU provision through illicit acquisition is not detected.	24	0.825	1.754×10^{-2}
Excess LEU production at an increased production rate is not detected.	16	0.725	1.469×10^{-2}
Excess LEU production at additional time is not detected.	16	0.725	1.469×10^{-2}
HEU production in connection of cascades mode is not detected.	18	0.175	1.464×10^{-2}
HEU production in reconfiguration mode is not detected.	18	0.175	1.464×10^{-2}
HEU production in batch recycling mode is not detected.	18	0.1625	1.265×10^{-2}
HEU production with add-on modular cascades is not detected.	18	0.1375	9.316×10^{-3}
NUF6 provision through illicit acquisition is not detected.	12	0.75	5.385×10^{-3}
LEU provision via diversion from LWRs is not detected.	8	0.9	5.193×10^{-3}
NUF6 provision via diversion from UCF is not detected.	12	0.725	5.116×10^{-3}
Undeclared NU conversion at declared UCF is not detected.	12	0.825	4.659×10^{-3}
LEU provision via diversion from FFP is not detected.	8	0.7	3.590×10^{-3}
LEUF6 provision through illicit acquisition is not detected.	4	0.75	2.988×10^{-3}
LEUF6 provision via diversion from GCEP is not detected.	4	0.5125	1.823×10^{-3}
Undeclared LEU conversion at declared UCF is not detected.	8	0.25	1.326×10^{-3}
Excess LEU production with add-on cascades is not detected.	16	0.125	1.210×10^{-3}

For Type B countries

Event Description	No of occurrence	Pr (BEi)	F-V importance
HEU production with add-on modular cascades is not detected.	18	1	1.01×10^{-3}
Clandestine UCF operation is not detected by ESWA/LIDAR at short distances.	20	1	4.24×10^{-4}
Clandestine UCF operation is not detected by ESWA/LIDAR at long distances.	20	0.825	4.24×10^{-4}
NU provision through illicit acquisition is not detected.	24	0.725	1.53×10^{-4}
HEU production in reconfiguration mode is not detected.	18	0.725	7.58×10^{-5}
HEU production in batch recycling mode is not detected.	18	0.175	5.76×10^{-5}
Excess LEU production with add-on cascades is not detected.	16	0.175	5.43×10^{-5}
LEU provision via diversion from LWRs is not detected.	8	0.1625	4.69×10^{-5}
Excess LEU production at additional time is not detected.	16	0.1375	4.28×10^{-5}
Excess LEU production at an increased production rate is not detected.	16	0.75	4.28×10^{-5}
HEU production in connection of cascades mode is not detected.	18	0.9	3.79×10^{-5}
NUF6 provision through illicit acquisition is not detected.	12	0.725	2.68×10^{-5}
LEU provision via diversion from FFP is not detected.	8	0.825	2.46×10^{-5}
NUF6 provision via diversion from UCF is not detected.	12	0.7	2.14×10^{-5}
Undeclared NU conversion at declared UCF is not detected.	12	0.75	1.92×10^{-5}
Undeclared LEU conversion at declared UCF is not detected.	8	0.5125	1.75×10^{-5}
LEUF6 provision through illicit acquisition is not detected.	4	0.25	1.27×10^{-5}
LEUF6 provision via diversion from GCEP is not detected.	4	0.125	8.20×10^{-6}



(a) Type A under Indirect Break-out Scenario



(b) Type B under Indirect Break-out Scenario

Figure 14.20 Fussell-Vesely Importance under Indirect Break-out Scenario

14.12 Conclusion

The actual application of the integrated methodology was carried out using success tree method and experts' judgments on basic events. Three types of quantitative analyses were performed to investigate the reliability of the success tree models that describe the success probabilities of HEU production. The results of this quantitative analysis are as follows:

- In general, under the assumption that a clandestine or declared GCEP is constructed, the proliferators' success probabilities are very high. This implies that the construction of a new GCEP should be prohibited.
- From the sensitivity analysis, it was noted that the application and development of ESWA technology for detecting clandestine GCEP would produce the highest benefit, albeit marginal.
- From the important analysis, the rankings of pathways were identified. This provides insight into the development of nuclear nonproliferation policy.

In assessing the proliferator's probability of success, the influence of intelligence community and the effect of information analysis were not considered. Consideration of these factors would result in a decrease of the top event probabilities. The success tree models may have produced better results if time delay factors, limited in the present study, could be accounted for.

CONCLUSION

CHAPTER 15 CONCLUSIONS AND RECOMMENDATIONS

15.1 Introduction

This study began with two questions: (a) how effective is the NPT regime in dealing with nuclear nonproliferation issue, and (b) what is the probability of proliferators successfully producing Highly Enriched Uranium (HEU) at Gas Centrifuge Enrichment Plants (GCEPs). Answers to the first question are essential to developing an integrated framework for evaluating the NPT regime effectiveness. The integrated framework reflects all factors affecting the nuclear proliferation using success tree method. This framework enables the evaluation of success probabilities for various proliferation scenarios on the front-end fuel cycle.

A quantitative assessment on the proliferation risk was performed with the integrated framework from the front-end fuel cycle point of view. The result shows that success probability of proliferators' producing HEU at GCEPs is very high for the scenarios developed in the present study. Within this integrated framework, the strengths and weaknesses of the NPT regime on the front-end of the nuclear fuel cycle were analyzed. Some important factors were further identified to prevent or reduce proliferation risks associated with GCEPs through the Fussell-Vesely importance measure and sensitivity analysis. This study recommends three approaches for reducing the proliferation threat of GCEPs as follows: (1) a nuclear elements control approach, (2) a multi-faceted approach (multiple-layers), and (3) a multidimensional approach that integrates legal- and technological capabilities.

15.2 NPT Regime Findings

Finding #1: Articles of the NPT are not explicitly written for preventing proliferation activities in Non Nuclear Weapon States (NNWS).

• Articles II and IV related to a nuclear weapons program are ambiguous. Thus, the interpretations of "manufacture of nuclear weapons" (Article II) and "inalienable right" (Article IV) are under dispute. Proliferators argue that they have the inalienable right to build questionable facilities. It is still in dispute whether the inalienable right should be insured unlimitedly or there should be a control limit, and based on what factors.

• Article X of the NPT allows a state to withdraw from the treaty without serious restrictions. Therefore, states can withdraw from the NPT at their convenience after they acquire uranium enrichment or plutonium reprocessing facilities in a licit way.

Finding #2: Only the UN Security Council has compliance-enforcing resources with regard to proliferation activities.

• The UN Security Council is the only organization that has robust compliance-enforcing measures with legal effects. However, imposing sanctions on proliferators is not as simple as it looks. Even if the IAEA concluded that a proliferation state is not in compliance with safeguards they signed, the IAEA cannot take any legally-binding measures to stop proliferation activities. These problems are shown in Figure 15.1

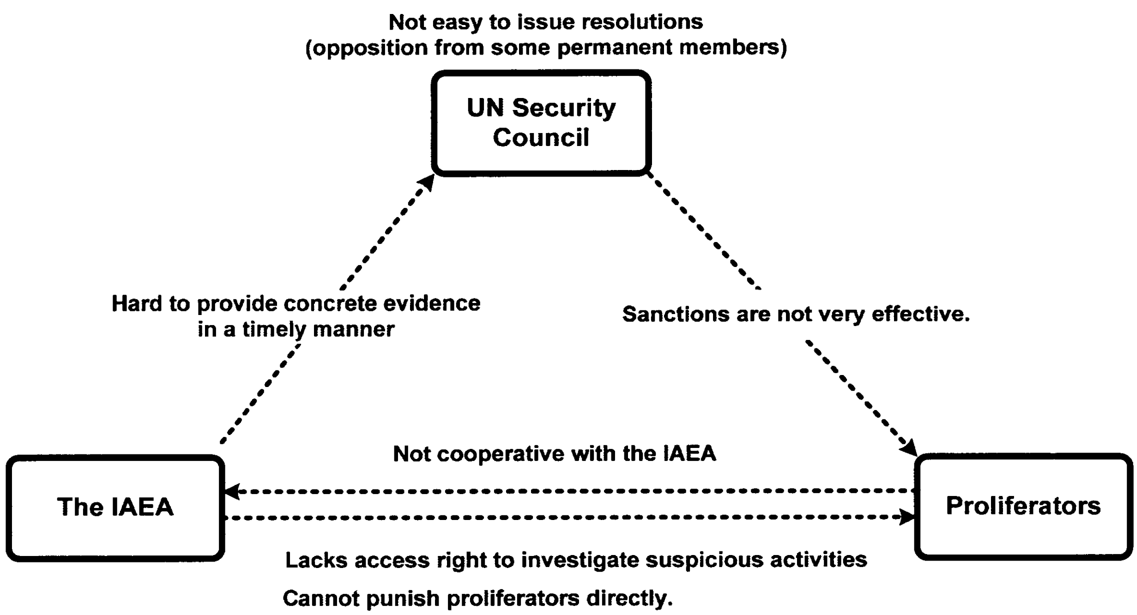


Figure 15.1 Problems of the Current NPT regime in Dealing with Proliferation Activities

• Establishing an international treaty would be required to make an international arrangement legally binding. However, this would be very challenging for several reasons: First, drafting and ratifying a treaty is a lengthy process. Second, legal effects of international treaties are not universal across different countries even after they are introduced. This is because international treaties, in general, can have legal effects after they are put into the form of legislation within each state.

15.3 HEU Production at GCEPs Findings

Finding #1: The NPT regime does not have legal authority to prohibit the construction of new GCEPs in NNWS.

There is no international institution in the NPT regime with authority to decide if a new enrichment plant may be built in NNWS. The IAEA's Comprehensive Safeguards Agreement (CSA) requests a state to report a newly-proposed facility as early as possible. But, the IAEA itself does not have the legal authority to disapprove a proposal. The issue of building a new GCEP can be resolved through the UN Security Council only if it is proven that a particular uranium enrichment project threatens the international peace and security. To that end, however, the IAEA should be able to provide clear evidence that the state concerned is in non-compliance with safeguards agreement.

Finding #2: The NPT regime does not have enough resources to control nuclear trade concerning the construction of new GCEPs.

• Weakness in controlling nuclear material trade

The two types of IAEA safeguards have weaknesses regarding control of undeclared Uranium Ore Concentrate (UOC) transfers. UOC that is to be used for non-nuclear purposes can be exempted from declaration in a safeguards application under Para 34 (a) and (b) of the CSA. The Additional Protocol (AP) addresses this loophole, by requiring notification of transfers of source material for non-nuclear use. Even under the AP, however, the IAEA depends on the cooperation of states when it wants to acquire information.[729] It is generally regarded that most of UOC is not of serious safeguards concern; however, it is possible that proliferators could process this type of material for its clandestine nuclear program.

• Weakness in controlling in nuclear equipment trade

The IAEA does not receive information about Dual-Use Items (DUI) reporting. Through the introduction of the AP, the IAEA receives information about the transfer of equipment or material Especially-Designed or Prepared for the processing, use, or production of special fissionable material (EDP), but the IAEA does not collect information about the trade of Dual-Use Items (DUIs).

• Weakness in controlling in nuclear technology trade

Nuclear technology is inherently hard to control because it is intangible and can be transferred via the internet. Also, most of nuclear technology required for a nuclear weapons program is readily available in many literatures. Even though the technology is out of date, it may suffice the requirement to build nuclear weapons.

• Weakness in Multilateral Export Control Regimes (MECRs)

The MECRs, including the Zangger Committee and the Nuclear Suppliers Group (NSG) do not include all possible states that can produce nuclear elements for a nuclear weapons program. In addition, the MECRs do not require member states to report denial information. Therefore, the NPT regime has very limited information about the proliferators' illicit attempts to acquire nuclear elements.

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[729] Under both CSA and AP, the international transfer of UOC is not under safeguards if it is for specifically for non-nuclear purposes, and if it is below 10 metric tons of UOC under the AP.

Finding #3: Safeguards effectiveness for declared nuclear facilities needs to be further strengthened.

• Complementary access via the AP should be generalized in order to enhance the IAEA's capabilities for detecting proliferation activities at declared UCFs and GCEPs.

Complementary access is crucial to detecting undeclared operation with add-on capacity at declared GCEPs and UCFs.

• Success probability of diverting declared nuclear material is still high because of the uncertainty associated with Material Unaccounted For (MUF).

MUF affects the efficiency and accuracy of Nuclear Material Accountancy (NMA). This may provide a favorable opportunity for proliferators in diverting declared nuclear materials, in particular, at GCEPs of large capacity.

• The IAEA needs more resources to widely use currently available verification technologies and to enhance the continuity of knowledge.

Technological level of various verification technologies is satisfactory. However, the IAEA lacks resources to deploy those available technologies. For example, three to four month-duration to obtain precise results through Destructive Assay (DA) may create an opportunity for proliferators. This is because the Safeguards Analytical Laboratory (SAL) is the only IAEA-owned facility for DA analysis.

Finding #4: The construction of new GCEPs in NNWS will pose significant threats to the NPT regime.

• Once GCEPs are constructed, there is little chance that the NPT regime can stop proliferation activities, if a proliferator decides to do so.

Detecting the operation of clandestine GCEPs is highly unlikely because of its high efficiency in enrichment operation. GCEPs do not release environmental signatures. In addition, a small GCEP could be built in any large industrial building. Thus, current technology for detecting clandestine GCEPs does not work at long distances in which IAEA inspectors are not given access to a state or near suspicious facilities.

Finding #5: Safeguarding Uranium Conversion Facilities (UCFs) creates a bottleneck opportunity in preventing HEU production.[730]

For proliferators, the possession of a UCF gives a high degree of freedom in providing uranium feed to GCEPs because a UCF produces UF_6 gas, which is the form of uranium used for enrichment operation at GCEPs. Thus, the enhanced control of UCFs could be effective in preventing the production of HEU.

[730] Only 8 states have UCFs (Brazil, Canada, China, France, Iran, Russia, UK, and USA).

As for the detection of clandestine facility operation, clandestine UCFs provide a higher chance of detection than clandestine GCEPs using ESWA and LIDAR technologies.

Finding #6: The IAEA's safeguard capabilities differ for declared and undeclared facilities (or material).

This difference in turn limits the ways in which information from each type of facility can be used. For example, verification information about declared GCEPs would incur further verification confirmation activities such as complementary access under the AP. On the contrary, verification information about clandestine GCEPs is limited to raising reasonable suspicion that would incur follow-up inspections at the suspicious facility.

15.4 Recommended Approaches for Strengthening the NPT Regime

15.4.1 Recommendation #1: Use of a Nuclear Elements Control Approach

The classification of nuclear elements into material, equipment, and technology will be very helpful for controlling nuclear trade in the NPT regime. This approach can be applied at different steps of a nuclear weapons program. Theoretically, proliferators cannot produce HEU unless, at least, one of these elements is controlled. Among these three elements, the control of nuclear material seems to be highly promising based on the quantitative study. Table 15.1 shows what NPT regime components are involved in the transfer of nuclear elements. One must note that the number of NPT regime components that are in place to control an element does not mean that the NPT regime is effective for that purpose.

Table 15.1 NPT Components with Measures for Controlling Nuclear Elements

NPT components	NPT	FMCT	IAEA safeguards		IAEA CPPNM	MECRs		UNSC 1540 Committee	PSI
			CSA	AP		ZC	NSG		
Material	X	X	X	X	X	X	X	X	X
Equipment	X			X		X	X	X	X
Technology				X			X	X	

Note: X denotes that corresponding NPT regime component has measures to control elements required for nuclear weapons program.

15.4.2 Recommendation #2: Use of a Multiple-Layers (or Multi-faceted) Approach

A multiple-layers approach throughout the different steps of a nuclear weapons program is recommended. As shown in Figure 15.2, all NPT regime components work at each phase in the production of HEU. A total of five layers are depicted in the Figure. These layers can be used as a decision-making framework to address the nonproliferation issues associated with GCEPs.

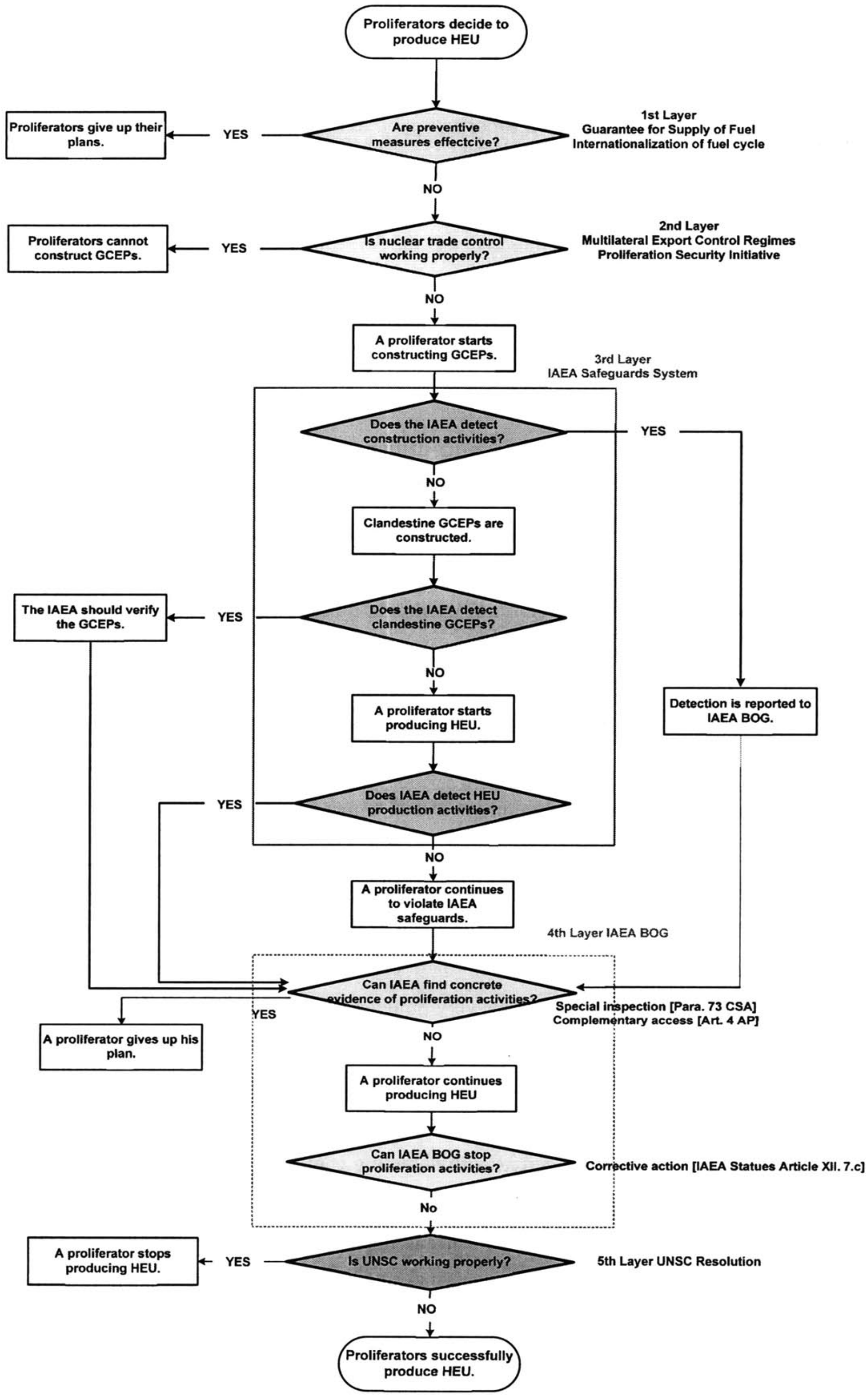

Figure 15.2 Multiple Layers to Prevent the Production of HEU

The prevention of clandestine production of HEU starts with persuading proliferators by guaranteeing the assurance of fuel supply through the internationalization of nuclear fuel cycle. This will not only provide a rationale for the IAEA to prohibit proliferators' construction of a new GCEP but also may persuade other states not to consider an option to build a new GCEP. The second layer can be banning nuclear elements trade through nuclear trade control via Multilateral Export Control Regimes (MECRs), the UNSC Resolution 1540, and Proliferation Security Initiatives (PSI). In parallel, the IAEA carries out monitoring operations in order to detect the construction and operation of clandestine GCEPs. In the case that the IAEA detects clandestine GCEPs and the proliferators do not comply with IAEA safeguards, the IAEA Board of Governors (BOG) and the UN Security Council will take measures to stop proliferation activities.

15.4.3 Recommendation #3: Use of a Multi-dimensional Approach

In the NPT regime, the use of technology is highly dependent on legal capabilities. Thus, a recommendation for increasing the NPT regime effectiveness should consider both perspectives.

• Cooperation with the intelligence community should be enhanced.

There is no single remote detection technology that can detect the operation of clandestine GCEP.[731] The benefits of further investment in remote detection technology are estimated to be marginal. However, the intelligence community has access to NTMs and HUMINT, which turned out to be a very efficient NPT regime component in revealing clandestine nuclear weapons programs. Thus, the IAEA's cooperation with the intelligence community is crucial to increasing the detection capabilities.

• Information collection and analysis capabilities should be enhanced.

In parallel, information management and analysis capabilities should be enhanced to compile all sources of information in an efficient manner. While there exists a large volume of data concerning possible proliferation activities, each source contains very limited information and little significance. To that end, the 'Physical Model' of the IAEA is very promising since it can integrate all types of data, producing meaningful information for detecting nuclear proliferation activities.

• Increasing legal capabilities associated with detecting clandestine GCEP operation

Legal constraints for applying ESWA/LIDAR/DIAL technologies can only be removed by a Board of Governor (BOG)'s Approval under the AP. In this regard, the universal application of the AP to the IAEA's member states is critical to increasing detection capabilities using currently available

[731] However, remote detection technologies can be used for: providing supplementary information for safeguards analysis and raising reasonable suspicion in order to warrant complementary access to the suspicious facilities.

technologies. Changing legal constraints is more likely to be achieved in the immediate future, allowing long-range GCEP detection that is currently not permitted under existing legal constraints.

15.5 Applicability of the Integrated Methodology and Future Work

The integrated methodology can be tailored to evaluate success probabilities of producing HEU in states with a different completeness level of the fuel cycle. With some modification, the methodology can be also applicable to evaluating success probabilities of producing weapons-grade plutonium at Plutonium Reprocessing Facilities (PRFs). A quantitative analysis using hierarchic-metrics was not performed in the present study. However, those metrics can be used for quantifying basic events in terms of probabilities without experts' judgment, if one can get access to data about previous inspections. In addition, a modeling tool that can simulate the time delay may produce more meaningful results.

APPENDICES

A. Quantification Criteria for Nuclear Proliferation Evaluation
B. Detection of Nuclear Weapons Tests
C. Status of MECRs
D. Measurement of UF6 Enrichment Ratio
E. Detection of Clandestine PRFs and GDPs
F. Evaluation of Thermal Satellite Imagery Applicability for Detecting a GCEP
G. Specification of IAEA Safeguards
H. Diversion of Nuclear Material from Various Reactors
I. Expert Opinion Questionnaire
J. Hierarchic Metrics

APPENDIX A: QUANTIFICATION CRITERIA USED FOR NUCLEAR PROLIFERATION EVLAUATION

Table A.1 Definitions and Methods for Quantification

Index	Components considered
STCI	Science and Technology Capacity Index includes three distinct domains of S&T capacity: (1) Enabling factors that help create an environment conducive to the absorption, retention, production and diffusion of knowledge, (2) Resources that can be devoted to S&T activities, which concerns the indicators that relate most directly to S&T capacity, (3) Embedded knowledge of science and technology and the extent to which researchers are connected to the global scientific community
KEI	The Knowledge Economy Index (KEI) takes into account whether the environment is conducive for knowledge to be used effectively for economic development. The KEI is calculated based on the average of the normalized performance scores of all 4 pillars related to the knowledge economy – (1) economic incentive and institutional regime, (2) education and human resources, (3) the innovation system, and (4) Information and Communication Technology (ICT).
HDI	The Human Development Index (HDI) is an index used to rank countries by level of "human development", which usually also implies to determine whether a country is a developed, developing, or underdeveloped country. The Human Development Index (HDI) combines four normalized measures of (1) life expectancy, (2) literacy, (3) educational attainment, and (4) GDP per capita for countries worldwide. It is claimed as a standard means of measuring human development—a concept that refers to the process of widening the options of persons, giving them greater opportunities for education, health care, income, employment, etc.
GDP	Gross Domestic Product
WGI	World Governance indicators (WGI) measures six dimensions of governance between 1996 and 2007: (1) Voice and Accountability, (2) Political Stability and Absence of Violence/Terrorism, (3) Government Effectiveness, (4) Regulatory Quality, (5) Rule of Law, and (6) Control of Corruption. In particular, 'political instability and absence of violence index' gauges the probability that a government 'will be destabilized or overthrown by possibly unconstitutional and/or violent means, including domestic violence and terrorism.

Table A.2 References for Indices

Index	Analysis	Publisher	Reference
STCI	Technology	RAND	Caroline S. Wagner, Edwin Horlings, and Arindam Dutta (2002), Can Science and Technology Capacity be Measured? <http://users.fmg.uva.nl/lleydesdorff/cwagner/Thesis/Chapter%20VI%20Capacity%20index.pdf>.
KEI		The World Bank	The World Bank, Knowledge for Development Program, KEI 2008 Rankings <http://info.worldbank.org/etools/kam2/KAM_page5.asp>
HDI		UNDP	UNDP-2007/2008 Report: Human Development Indices <http://hdr.undp.org/en/media/HDI_2008_EN_Tables.pdf>
GDP	Economy	IMF	GDP2007 <http://en.wikipedia.org/wiki/List_of_countries_by_GDP_(PPP)>
GDP per capita		CIA	GDP per capita 2007, CIA World Factbook <https://www.cia.gov/library/publications/the-world-factbook/rankorder/2004rank.html>
WGI	Domestic Politics	The World Bank	WGI 2007 <http://info.worldbank.org/governance/wgi/index.asp> The World Bank, Governance matters 2008, The Worldwide Governance Indicators (WGI) Project, WGI includes Voice and Accountability, Political Stability and Absence of Violence, Government Effectiveness, Regulatory Quality, Rule of Law, and Control of Corruption

APPENDIX B: DETECTION OF NUCLEAR WEAPONS TESTS

The detection of nuclear weapons test involves three kinds of information.

- Detection of occurrence including information about location,
- Measurement of nuclear explosive yield, and
- Subsequent evaluation of success or failure of the test

B.1 Detection of Nuclear Test Occurrence

Zhang (2007) suggests that the best alternative way to estimate nuclear explosion is to analyze the seismic data if on-site measurement is not available.[732] In order for CTBT verification to be successful, radioactivity must be detected and the risk of false alarms must be taken into consideration. As we saw in case of North Korea nuclear test, one method alone cannot prove whether or not there was an explosion. Seismic observations coupled with radionuclide analysis with Atmospheric Transport Simulation (ATS) could make the distinction.

WAES: As for the detection of nuclear weapons tests, two kinds of information about nuclear weapons tests can be obtained through WAES coupled with Atmospheric Transport Simulations (ATS).[733] One is the identification of nuclear test occurrence and the other is the location of nuclear explosion. This is possible because nuclear explosions are most likely to entail the release of gaseous fission products such as Xe-135, Xe-133m, Xe-133 and Xe-133m.[734] Yet, xenon gases can be released during normal nuclear reactor operations. Thus, the inspectors must be capable of distinguishing between emissions from reactors and releases from nuclear explosions. To this end, isotopic ratios analysis can be utilized by modeling how the ratio of Xe-133m/Xe-133 develops over time after the explosion. Nuclear explosion tests will result in the ratios well above the reactor domain and render source discrimination possible even five days after the explosion. Ringbom et al (2007) demonstrated that isotopic ratios can be utilized for source discrimination, even if only the two different isomers Xe-133 and Xe-133m were quantified per sample.[735]

Satellite Imagery: As for the detection of nuclear weapons tests, satellites are limited because they cannot monitor for 24 hours a day, but it can provide some information about preparation activities for nuclear weapons test. The U.S. has a classified system of satellite sensors for detecting nuclear detonations, which is called Nuclear Detonation Detection System (NDS). NDS uses x-ray, optical, and electromagnetic pulse sensors integrated on operational Global Positioning System (GPS) and Defense Support Program (DSP) satellites to detect nuclear weapons tests. This system is the successor of VELA satellites.[736]

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[732] Hui Zhang, "Revisiting NK's Nuclear Test," *China Security* 3, no. 3 (Summer 2007).

[733] Atmospheric Transport Simulations (ATS) was used to identify North Korea's nuclear tests to relate detected radioisotopes to the geographic region of the explosion. Ibid.

[734] Even if nuclear tests are designed for full containment, there is always a risk that the containment fails and then radioactivity is released unintentionally into the atmosphere. Atmospheric and underwater tests generally release a larger amount of radioactivity than underground tests and will be easily detectable. For detection of trace gases from underground tests, see C.R. Carrigan et el., "Trace Gas Emissions on Geological Faults as Indicators of Underground Nuclear Testing," *Nature* 382, no. 6591 (1996)., pp.528-531.

[735] A. Ringbom, K. Elmgren, and K. Lindh, "Analysis of Radioxenon in Ground Level Air Sampled in the Republic of South Korea on October 11-14, 2006," (FOI-R-2273-SE, Stockholm: FOI, 2007).

[736] The VELA satellites were the original system first launched in 1963 used to was developed to monitor compliance with the Partial Test Ban Treaty until the 1980s. They were equipped with non-imaging silicon photodiode sensors and electromagnetic pulse sensors. The former monitors light levels over sub-millisecond intervals, whereas the latter detects electromagnetic pulse from a nuclear explosion.

B.2 Evaluation of Nuclear Weapon Yield

Once the occurrence of nuclear explosive tests is identified, it will be followed by estimate on nuclear explosive yield and subsequent conclusion on whether it was successful. The types of nuclear explosive energy released should be identified to provide a theoretical background to measure nuclear explosive yield and values are shown in Table C.1. The ***nuclear explosive yield***, which is the amount of energy after nuclear explosion, can be estimated in various ways as shown in Table C.2.

Table B.1 Energy Release Depending on Different Forms after Explosion[737]

<table>
<tr><th>Form</th><th>Nuclear fission weapon</th><th>Thermonuclear weapon</th></tr>
<tr><td>Air blast and shock</td><td rowspan="3">85%</td><td rowspan="4">95%</td></tr>
<tr><td>Thermal radiation</td></tr>
<tr><td>Heat</td></tr>
<tr><td>The initial nuclear radiation</td><td>5% (within one minute after detonation)</td></tr>
<tr><td>The residual nuclear radiation</td><td>10%</td><td>5%</td></tr>
</table>

Table B.2 Different Methods to Measure Nuclear Weapons Yield

<table>
<tr><th>Sources</th><th>Methodology</th><th>Reference</th></tr>
<tr><td>Shock wave[738]</td><td>Measure the strength of shock wave by dropping small pieces of paper in the air and how far they were moved by the shock wave of the explosion.</td><td>Fermi[739]</td></tr>
<tr><td>Energy released</td><td>Calculate the energy released with the radius of the blast, the density of the air, the time after the detonation, and the ratio of the specific heats of air</td><td>Taylor [740]</td></tr>
<tr><td>Light flash</td><td>Estimate the light flash of an atmospheric nuclear explosion for an optical detection and yield determination</td><td>Barasch[741]</td></tr>
<tr><td>Radio -chemistry</td><td>Measure nuclear debris of radioactive isotopes produced in the detonation. (This is regarded as the most accurate yield measurement method and does not require any electronics for data gathering for analysis.)</td><td rowspan="2">MCTL[742]</td></tr>
<tr><td>Seismographs</td><td>Measure ground motions.
(This is a faster test but less accurate and limited in collecting a large quantity of data enough for nuclear weapon developers.)</td></tr>
</table>

[737] Samuel Glasstone and Phillip Dolan, "The Effects of Nuclear Weapons," (Washington D.C.: U.S. Department of Defense/U.S. Energy Research and Development Administration, 1977).

[738] A shock wave is a pressure wave initiated by the rapid expansion of hot, compressed gases after explosion. Ibid.

[739] LarryCalloway, *The Trinity Test: Eyewitnesses July 16, 1945* (May 10 2005 [cited Nov. 11 2008]); available from http://larrycalloway.com/historic.html?_recordnum=105.

[740] Geoffrey Taylor, "The Formation of a Blast Wave by a Very Intense Explosion: I. Theoretical Discussion," *Proceedings of the Royal Society of London, Series A, Mathematical and Physical Sciences* 201, no. 1065 (1950)., pp.159-174.

[741] Guy Barasch, "Light Flash Produced by an Atmospheric Nuclear Explosion," (LASL-79-84, Los Alamos Science Laboratory, Nov. 1979). He used the light-flash signature of atmospheric nuclear test between time after detonation and total thermal power with two-peaked character and very large radiation during the second peak.

[742] A degree of uncertainty lies in the conversion of seismic magnitude into explosive yield due to many different factors such as variations in geological structure, the type of rock of the explosion cavity, and emplacement method of explosion. This is well-explained in "Seismic Verification of Nuclear Testing Treaties," Office of Technology Assessment, OTA-Office of Technology Assessment U.S. Congress, *Seismic Verification of Nuclear Testing Treaties Office of Technology Assessment (OTA-ISC-361)* (Washington DC: US Government Printing Office, May 1988).

B.3 Evaluation of Nuclear Tests

For estimating of whether a nuclear test is successful or not, two kinds of weapon yields, nominal or explosive yield and design yield should be compared. The results can be classified as a success, a fizzle, or a failure. A fizzle is generally defined as the smallest possible yield resulting from pre-detonation. A nominal yield is the actual yield of the nuclear explosion while design yield is the planned yield of the explosion. Seismic magnitude values can be translated into yields that differ by a factor of ten. According to this methodology, 1 kiloton of nuclear explosive yield is estimated as an average magnitude value of 4.2 Mb (magnitude of body wave) with an uncertainty factor of two. Zhang (2007) suggests that the success of nuclear explosion test can be analyzed based on the Mark's simplified model of the implosion design weapons behavior and von Hippel and Lyman's calculations of the probabilities of different yields.[743] However, it should be noted that a low-yield test might imply that a proliferator seeks for a nuclear warhead that can be mated for a missile, i.e., warhead miniaturization.

B.4 CTBT's Verification System[744]

The CTBT's verification system comprises three elements: International Monitoring System (IMS), International Data Center (IDC) and On-Site Inspections (OSI). The IMS consists of four networks with different sensor technologies. International monitoring system is a network that can detect signals that are indicative for nuclear explosions, as well as to identify and to locate nuclear explosions underground, underwater or in the atmosphere. The IMS network will consist of 321 stations in order to monitor the whole globe. 250 of these have already built by March of 2008. It has sub-networks with four different sensor technologies. At present, a few kiloton is enough to detect nuclear weapons tests, even if it is exploded underground.

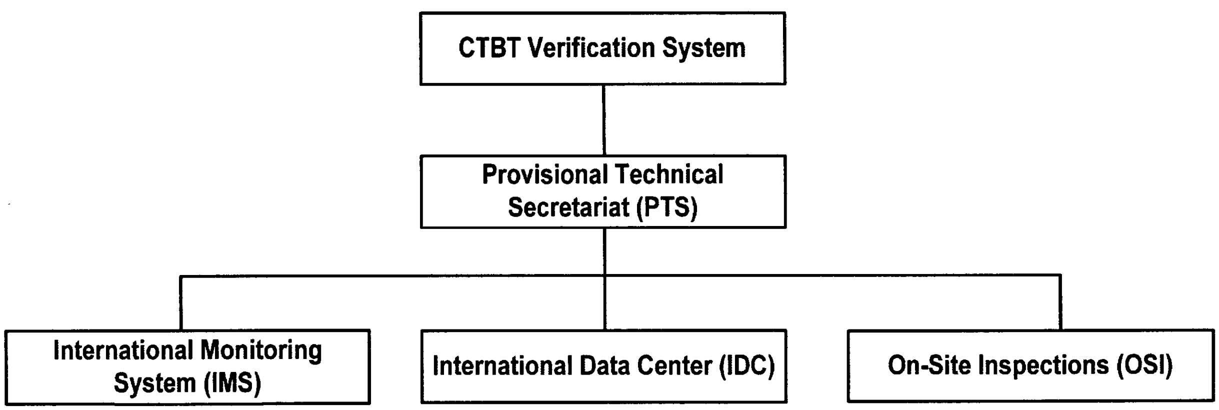

Figure C. 1 Verification System of CTBT

743 Zhang, "Revisiting NK's Nuclear Test.";Mark, "Explosive Properties of Reactor-Grade Plutonium."; and F. Von Hippel and E. Lyman, "Appendix: Probabilities and Different Yields," *Science and Global Security* 4, no. 1 (1993)., pp.125-128.

744 Bösenberg and Kalinowski, "Detecting Atmospheric UF6 and HF as Indicators for Uranium Enrichment."; M. Kalinowski, "Remote Environmental Sampling for the Detection of Clandestine Nuclear Weapons Production and Testing" (paper presented at the ESARDA Training Course for Nuclear Safeguards and Nonproliferation, Ispra, April 14-18 2008).

Table B.3 Sub-Network of CTBT's IMS

Techniques	Number of stations	Description
Seismic	• 50 primary and 120 auxiliary seismological stations	•Conclusion can be made if a seismic event was caused by an explosion or by an earthquake. •Limitation: in case of low level of explosion falls within the range of 0.5-0.8 kt TNT, it is impossible to reach a conclusion on whether the explosion is caused by chemical explosives or by a nuclear one. Thus, seismic signals cannot b used to make this level of distinction.
Hydro-acoustic	• 11 stations to monitor all oceanic waters	•Six hydrophone stations and five supplement T-phase stations located on ocean islands. •Hydrophone stations will be located offshore from mid-ocean islands. •T-phase stations are seismic stations that record signals that mainly propagate through the oceans and located near-shore typically on mid-ocean islands. [745]
Infrasound	• 60 infrasound stations	The infrasound network will be equipped with microbarographs in order to measure small changes in the air pressure.
Radio-nuclides	• 80 radionuclide stations • 80 particulate stations [a]	•16 radionuclide laboratories •Process [1] The radionuclide stations will take daily samples, conduct the measurement in the field and send the data to the IDC in Vienna. [2] Upon receipt, the pre-analysis is done automatically and then reviewed by analysts for quality control. [3] The results are sent to the member states and stored in a database. •Minimal detection requirement of ***radioxenon monitoring system***: 30 μBq/m3 and 1 mBq/m3 for Xe-133.

Note: [a] 40 noble gas systems are collocated with particulate stations

[745] Jeffrey Hanson, "Operational Processing of Hydroacoustics at the Prototype International Data Center," *Pure Applied Geophysics* 158 (2001)., pp.425-456.

APPENDIX C: STATUS OF MECRs

Table C.1 Current Status of MECRs [As of April 2009]

	ZC[746]	NSG	WA
No. of member states	**37**	**45**	**41**
Meeting	Annually in Vienna	Annual Plenary meeting	Annual Plenary Meeting in December
Subsidiary bodies	N/A	•Consultative Group Meeting •Information Exchange Meeting •Working Group Meeting	•General Working Group •Experts Group •Licensing and Enforcement Officers Meeting
Chairmanship	Selection by consensus (but not annually)	Rotates annually	Rotates annually
Office	None	None	Secretariat in Vienna
Conditions of supply of export	•Non-explosive assurance •Re-transfer provision	•Strengthened re-transfer provision[747]: government-to-government assurance •Nonproliferation principle •Full-scope safeguards requirement for exports[748]	N/A
Member qualification	a member of the NPT	not require to be a member of the NPT	States that meet Participation criteria set by the WA
Control items list	Annex to INFCIRC/209	INFCIRC/254/Part 1 and 2	
	Trigger List	NSG Guidelines Part1: The Export of Nuclear Material, Equipment and Technology Part 2: Transfers of Nuclear-Related Dual-Use Equipment, Materials, Software and Related Technology	•List of Dual-Use Goods and Technologies - Part 1 to 9, - Sensitive List -Very sensitive List •Munitions Lists
	•Especially designed or prepared items (EDP) •Heavy water	Dual-Use Items (DUI)	Transfers of Conventional arms and dual-use goods and technologies.
Application	Transfers to NNWS not party to the NPT	Transfers to all NNWS regardless of NPT membership possession	Transfers to all states and non-state actors

746 Personal communication with Mr. Graham Styles (UK mission and the first secretary to the ZC) via e-mail on Nov. 3rd, 2008.
Meeting frequency-Meeting of the Committee tend to take place annually, usually in Oct. or Nov. If necessary, there can be a second meeting in spring. The Chairmanship-The Chairmanship does not rotate annually unlike the NSG. The Chair is selected by consensus of the ZC members, on a personal/individual basis rather than on the grounds of nationality. Secretary of the Committee-The UK mission in Vienna traditionally provides the Secretary of the Committee and serves as a modest Secretariat by maintaining an archive of key documents and by issuing communications to members. The Secretary circulates to members the official record of meetings and other official ZC documents. Meeting venue: The Austrian authorities provide the venue for official ZC meetings

747 In 1994, the NSG also strengthened its re-transfer provisions to require government-to-government assurances to support the stipulation that a supplier's consent be obtained for the re-transfer of trigger list from any State that does not require full-scope safeguards as a condition of supply.

748 However, both ZC and NSG apply full-scope safeguards to NNWS as a condition of supply for trigger list items.

The Figure below shows the flow of trade information in Multilateral Export Control Regimes (MECRs). As necessary, the IAEA can request MECRs to provide information about nuclear trade. However, MECRs has no obligation to share information with the IAEA.

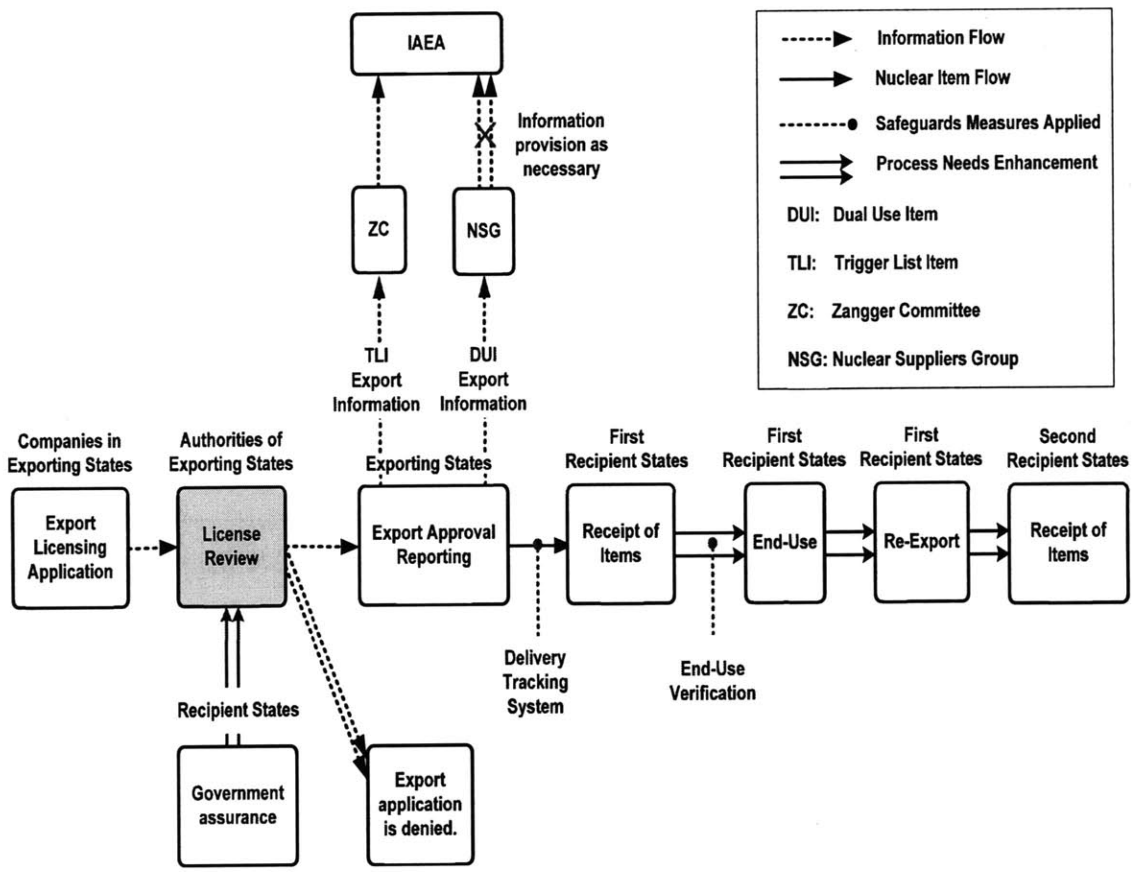

Figure C.1 Nuclear Trade Information Flow in the NPT Regime

APPENDIX D: MEASUREMENT OF UF6 ENRICHMENT RATIO

D.1 Theory of UF6 Gas Enrichment Ratio Measurement

The enrichment of the UF6 process gas in the header pipe is calculated using the following equation: [749]

$$E = K \times \frac{R_{186(Total)} - R_{186(BG)}}{R_{XRF}}$$

where

E = U-235 enrichment (in weight %) of the process gas,

$R_{186\,(Total)}$ = U-235 185.7 keV total count rate (c/s) (gas + deposit + room background),

$R_{186\,(BG)}$ = U-235 185.7 keV background count rate (c/s) (deposit + room background),

R_{XRF} = Uranium 98.4 keV Ka1 x-ray count rate (c/s/mCi) induced by 57CoXRF source, and

K= Calibration constant

Equation for the uncertainty in the enrichment is given by:

$$\Delta E = \sqrt{E^2[(\frac{\Delta R_{XRF}}{R_{XRF}})^2 + (\frac{\Delta K}{K})^2 + (\frac{K}{R_{XRF}})[(\Delta R_{186(Total)} + (\Delta R_{186(BG)})^2}$$

Statistical error comes from line separation and detector resolution. Systematic error of HRGS comes from variations in gamma ray spectroscopy detection efficiency, uncertainties in the spectral background, and the uncertainty of the branching ratios.[750]

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[749] P. L. Kerr et al., "IAEA Verification Experiment at the Portsmouth Gaseous Diffusion Plant: Report on the Cascade Header Enrichment Monitor, LA-13557-MS.".

[750] Stephane F. Terracol et al., "Ultra-High Resolution Gamma-Ray Spectrometer Development for Nuclear Attribution and Non-Proliferation Applications".

D.2 Mass Spectrometry for Measuring the UER of UF6 gas

Table F.2 Applications of Different Mass Spectrometers for Isotopic Composition Analysis[751]

Material Type	U in solution			U or U Oxides	UF_6 gas	Pu in solution	Pu or Pu-oxides	Other actinides
	U-235/U-238	U^{234}/U-238	U^{236}/U-238					
AMS			O					
ICPMS	O	O	O	O		Ox	O	O
GSMS					O			
RIMS		Δ	Δ					
SIMS				O			O	
TIMS	O	O	O	O		O	O	O

Notes
[a] Accelerator Mass Spectrometry (AMS), Inductively Coupled Plasma Mass Spectrometry (ICPMS)
Gas Source Mass Spectrometry (GSMS), Resonance Ionization Mass Spectrometry (RIMS)
Secondary Ion Mass Spectrometry (SIMS), Thermal Ionization Mass Spectrometry (TIMS)
[b] O: Fully applicable. Δ: Partially applicable.

[751] I.T. Plazner, "Modern Isotope Ratio Mass Spectrometry", published by John Wiley & Sons, 1 edition January 1, 2001, ISBN-13; 978-0471974161

APPENDIX E: DETECTION OF CLANDESTINE PRFs AND GDPs

E.1 Detection of Plutonium Reprocessing Facilities (PRFs)

[1] Direct Detection of PRFs

Satellite Imagery for PRF Detection: It would be difficult to detect a small size PRFs using Visible and Near-Infrared (VNIR) imagery. Using satellite imagery in the Thermal Infrared (TIR), the detection of thermal signatures emanating from PRFs would be very difficult because they do not have significant thermal signatures. However, it is estimated that the United States has satellite capability to detect them.[752]

Infrastructure features of PRFs that can be observed with high resolution satellite VNIR imagery include a very high stack (or its shadow); a long 'canyon-like" building (or with vent); some holding ponds or reservoirs for waste of sludge; security perimeter; railroads, roads; an isolated site, etc.[753]

ESWA for PRF Detection: The feasibility of detecting clandestine PRF was proven through study using both atmospheric transport modeling[754] and field tests.[755] There are several environmental signatures for PRFs such as Kr-85, I-129, Sr-90, Cs-137, Ru-106, and T-3.[756] These gases are among volatile radionuclides released during the chopping phase in the reprocessing process. Among these signatures, krypton-85 is the most suitable tracer of PRFs at long distances, whereas I-119 seems to be the most promising tracer for short-range detection.[757] Field tests have shown that Kr-85 can be detected reliably at distances on the order of one hundred kilometers downwind from small PRFs by atmospheric Kr-85 plumes.[758]

[2] Indirect Detection of PRFs: Heavy Water Reactors (HWRs) are one of the most efficient reactors for producing a high quality of plutonium from natural uranium. In addition, HWRs can be used to produce tritium. HWRs use high purity heavy water, which exists in low concentration in nature and is produced at Heavy Water Production Plants (HWPPs). HWPPs typically use a dual-temperature water-hydrogen sulfide exchange process (Girdler Sulfide process-GS) as the primary process to enrich the deuterium from 0.015 percent to between 10 and 30 percent deuterium and finally use water distillation

752 James Martin Center for Nonproliferation Studies (CNS), *NWFZ Clearinghouse*.
753 Zhang, "Should and Can the FMCT Be Effectively Verified?."
754 D. Youn, D. Wuebbles, and M. Kalinowski, "Global Modeling of Atmospheric Krypton-85 Concentrations," *INESAP Information Bulletin* 27 (Dec. 2006)., pp.13-16. M. Kalinowski, J. Feichter, and O. Roβ, "Atmospheric Krypton-85 Transport Modeling for Verification Purposes," *INESAP Information Bulletin* 27 (Dec. 2006)., pp.17-20.
755 Kalinowski, Daerr, and Kohler, "Measurements of Krypton-85 to Detect Clandestine Plutonium Production."
756 Stafano Vaccaro, "Methods for the Detection of Undeclared Plutonium Production Facilities," *ESARDA Bulletin*, no. 37 (Dec. 2007)., pp.70-74 and Argonne National Laboratory, *Environmental Consequences Of. And Control Processes For. Energy Technologies* (Park Ridge, NJ: Noyes Data Corp., 1990).
757 Vaccaro, "Methods for the Detection of Undeclared Plutonium Production Facilities."
758 Bösenberg and Kalinowski, "Detecting Atmospheric UF6 and HF as Indicators for Uranium Enrichment."

method to get reactor-grade heavy water, which is 99.7 percent deuterium. Throughout these processes, the poisonous hydrogen sulfide (H_2S) gas is leaked from the plant.[759]

E.2 Direct Detection of Clandestine GDP

Satellite imagery can play a role in detecting a Gaseous Diffusion Plant (GDP) because of its large size and thermal signature. Infrastructure features of GDP that might be observable from high resolution satellite imagery include: Large area (roof) process buildings (the roof of most building have ventilation shafts); cooling towers or a nearby river or lakes; a nearby fossil fuel power plant; large electric switchyard (substation); waste management and disposal facilities; security perimeter; railroads, roads; an isolated site, etc.[760] There are also several signatures in association with the operation, including the water-vapor plume rising from the cooling tower that results from the slight super-saturation of air as it emerges; and thermal signature of the hot roof of the enrichment building as well as the cooling towers. This is because the lowest UF_6 temperature in a GDP must be safely above the UF_6 condensation or freezing temperature. The temperature of the compressors containing UF_6 must be kept higher than that of ambient air.[761]

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[759] Zhang, "IAEA-SM-367/16/01".
[760] Zhang, "Should and Can the FMCT Be Effectively Verified?.", pp. 50-55.
[761] Zhang, *FMCT Verification: Case Studies*.

APPENDIX F: EVLAUATION OF TIR APPLICABILITY FOR DETECTING A GCEP

The question may arise whether Thermal Infrared Imagery (TIR) from satellites can detect the operational status of clandestine nuclear facilities. Unfortunately, there is no straightforward way of knowing whether TIR can detect a target that has a higher temperature than its background. Many factors must be carefully considered to answer this kind of question.

There are three limitations in applying TIR for non-proliferation purposes. First, in order to detect the operation of a clandestine nuclear facility, one must detect an anomaly or change in temperature. This means that an exact background value should be established, spatially or temporally. However, the background of a target is subject to change over time. The uncertainty of this "background" may be considered the first limiting factor. Second, the target does not always fit completely inside one pixel. Third, satellites utilize radiometers instead of thermometers as thermal sensors, measuring radiance instead of temperature. Temperature and radiance have a non-linear relationship. Sometimes, temperature can be inferred indirectly through Planck's function, using this non-linear functional relationship between radiance and temperature and wavelength.

In order to evaluate whether thermal imagery could detect the operation of a clandestine facility, information about the background and the target must be clearly defined such as (a) mean value and standard deviation of the background temperature; (b) mean value and standard deviation of the target temperature; and (c) the size of the target.

As for the detection of a clandestine GCEP, we can make a very rough analysis using (a) a minimal temperature difference that allows the detection of thermal differences under a given GCEP footprint or (b) TIR's capability requirement for detecting a given specification of a GCEP such as a temperature release and the size of footprint.

Let us assume the following:

[1] A TIR has a thermal spatial resolution of 1 km and a Thermal Sensitivity (TS) of 0.05 °K.

[2] A GCEP has the size of 200 m x 200 m[762]

[3] The temperatures of the background and the target are at steady-state

[4] Clear-sky conditions

Under these assumptions, if we calculate the RTD using inequality (7.7) in Chapter 7, the minimum detectable RTD for the facility is obtained at 1.25 °K RTD as follows:

$$\frac{0.2(km)*0.2(km)}{1(km)*1(km)} \geq \frac{0.05(°K)}{RTD(°K)}$$

[762] This corresponds to the estimated footprint of Fuel Enrichment Plant (FEP) at Natanz, Iran. Glaser, *Making Highly Enriched Uranium*.

If a more realistic case is chosen, it can be assumed that a GCEP capable of an annual HEU production of 25 kg has a footprint of 160 m^2. If one wants to detect the operational status of this facility with Landsat 5 or 7 (TS of 0.5 °K and 60 m spatial resolution), the minimal detectable RTD is obtained at 11.25 °K using the following calculation:

$$\frac{12.65(m)\times 12.65(m)}{60(m)\times 60(m)} \geq \frac{0.5^{\circ}K}{RTD\,(^{\circ}K)}$$

It is well known that a temperature increase in association with the operation of a GCEP is much smaller than 11.25 °K. Thus, we conclude that the operational status of a clandestine GCEP cannot be detected with the most advanced TIR loaded onto contemporary CSI.

Again, the application of TIR imagery is highly dependent upon many factors and uncertainties. However, this rough analysis may explain how TIR can be applicable to detecting thermal abnormalities.

APPENDIX G: SPECIFICATION OF IAEA SAFEGUARDS

Table G.1 Multi-level Scheme for Detection of Falsification by the IAEA

Approach	Definition		Reference
Two-level approach [a]	Level 1 Measurement	•Detection of large falsifications •Easily performed but has relatively poor accuracy and precision	John Sanborn (1984)
	Level 2 measurement	•Detection of small falsifications •Performed with higher accuracy and precision	
Three-level approach	Gross defect	An item or a batch that has been falsified to the maximum extent possible so that all or most of the declared material is missing.	STR-261(1991) [b] IAEA Glossary 2001
	Partial defect	An item or a batch that has been falsified to such an extent that some fraction of the declared amount of material is actually present.	
	Bias defect	An item or a batch that has been slightly falsified so that only a small fraction of the declared amount of material is missing.	

Notes
[a] These measurements types are called attribute measurements and variables measurements in the attribute mode.
[b] Jeach, J. L., and M. Russell. "Algorithms to Calculate Sample Sizes for Inspection Sampling Plans, STR-261, Rev.1 ." IAEA, Mar. 1991

Table G.2 History of IAEA's Detection Goals

Period	Description	Reference
1970s and 1980s	**Goals for material accountancy verification** •For planning purposes, the probability of the detection of the absence of a SQ of nuclear material by accountancy measures is normally set at **0.90-0.95.**	IAEA/SG/INF/1 Rev.1 IAEA Safeguards Glossary, 1987
Since 1990	**Safeguards criteria** •Safeguard criteria are used both for planning the implementation of verification activities and for evaluating the results therefrom. •Some of these goals were revised downward for less sensitive nuclear materials (LEU, NU and DU)	IAEA Glossary 2001

Table G.3 The Safeguards Criteria for Detection of the Diversion of 75 kg of U-235 Contained in LEU, NU and DU within One Year (1990)

Facility and Nuclear Material		Detection Likelihood			Remarks
		Gross	Partial	Bias	
GCEP		Medium (50%)	Medium (50%)	Medium (50%)	IAEA-CN-148/98 (2006)[c]
NU conversion		Medium (50%)	Low (20%) [b]	-	Depending on physical form
LEU FFP	LEU	Medium (50%)	Medium (50%)	Medium (50%)	Depending on physical form
	NU	Medium (50%)	Low (20%) [b]	-	Depending on physical form
	DU	Medium (50%)	-	-	-
LWR Reactors	Fresh LEU fuel	Medium (50%)	-	-	Item counting or serial number identification
	Other nuclear material consisting of indirect-use material	Medium (50%)	-	-	Item counting

Notes
[a] 'Safeguards criteria' is defined in IAEA Glossary, p.25.
[b] The partial defects detection probability of 20% for these two cases applies to UF6 in cylinders. Some other forms are verified with a partial defects detection probability of 50%, while other forms are not verified at all for partial defects.
[c] W.Bush et al. "Model Safeguards Approach for Gas Centrifuge Enrichment Plants, IAEA-CN-148/98." 2006.

Table G.4 Definition of Effectiveness and Efficiency of Safeguards

Reference	Definition
IAEA safeguards glossary (1997)	Effectiveness (of IAEA safeguards implementation if a measure of the extent to which IAEA safeguards activities are able to achieve the safeguards objectives [paragraph 127]
	Efficiency (of IAEA safeguards operation) is a measure of the productivity of IAEA safeguards, i.e., how well the available resources (manpower, equipment, money) are used to fulfill the IAEA's part in the implementation of safeguards. [paragraph 130]
Peter Friend (2008)	The effectiveness of a safeguards measure – it relates to whether an operator is deterred from carrying out illicit activities by it. If he is not then it is not very effective.
	The efficiency of a safeguards measure– it relates to whether it gives value for money. One has to compare different measures and chose the one that gives the best value for money.

Note: For a quantitative modeling concerning safeguards effectiveness and efficiency, see

Table G.5 Three Levels of Defects in Accountancy Analysis[763]

Defects	Main stratum / material type	UER Measurements	CEMO	Example	Method codes [a]	Relative error ranges for total measurement uncertainty (δ_i)	Relative Standard Deviation (RSD)[764]
Gross	LEU/NU/ DU in cylinders	Gamma -ray NDA	On feed and tails headers	No U in a Cylinder	H	$0.0625 < \delta_i \le 0.125$	~25-50%
	LEU/NU/DU (waste)						
Partial	LEU/NU/ DU in cylinders		On product headers	•Lowered U-235 content •Part of U is missing	F	$0.010 < \delta_i \le 0.0625$	~5-12%
Bias	LEU/NU/ DU in cylinders	Sampling and DA (TIMS) [b]	N/A	Lowered U-235 content bias	E (NDA)	$\delta_i \le 0.01$	N/A
					D (DA)		

Notes
[a] E and D use the most accurate NDA such as K-edge densitometer and the most accurate DA method, respectively.
[b] TIMS stands for Thermal Ionization Mass Spectrometry.

763 Boyer, *Safeguards Approaches for Gas Centrifuge Enrichment Plants: LANL Safeguards Systems Course - Pilot 2008.*
764 Jae Jo, Radio Frequency Identification Devices: Effectiveness in Improving Safeguards at Gas Centrifuge Uranium Enrichment Plants, presented to the INMM, Tucson, AZ, (July 2007)

Table G.6 Differences of Legal Capabilities between INFCIRC/153- and INFCIRC/540-type Safeguards Agreement

	Provision of information						Inspectors access				
	Nuclear material		Equipment	R & D	Facility or location under safeguards		Environmental sampling			CA	Multiple -entry visas
							Declared facilities		Outside declared facilities		
	Uranium Ore Concentrate (UOC)		Export	Nuclear fuel cycle	LOF	Mine & concentration plants	Strategic points	Non-strategic points	ESWA		
	Initial declaration [f]	International transfer for non-nuclear purposes									
CSA	X [34 (a),(b)]	X	X	X	O [49]	X	O	X	X	X	X
AP	*O [2.a.(vi)]*	O [2.a.(vi)] [e]	O [2.a.(ix) and Annex II]	O	O [g]	*O [2.a.(v)]*	O	O	O	O [4]	O [12]

Notes

[a] Comprehensive Safeguards Agreement (CSA), Additional Protocol (AP)

[b] Environmental Sampling over Wide Area (ESWA), Complementary Access (CA)

[c] The location, operational status, and the estimated annual production capacity.

[d] Boxes in ***Italic*** are not subject to detailed Nuclear Material Accountancy (NMA).

[e] Source material which has not reached the composition and purity suitable for fuel fabrication or for being isotopically enriched in quantities exceeding ten metric tons of uranium.

[f] Any nuclear material of a composition and purity not suitable for fuel fabrication or for being isotopically enriched, specifically for non-nuclear purposes.

[g] Under CSA, only a general description about NMA is requested, where as operational status is required under the AP.

[h] O and X stand for existence and non-existence of stipulating articles or paragraphs, respectively.

APPENDIX H: DIVERSION OF NUCLEAR MATERIAL FROM VARIOUS REACTORS

H.1 Characteristics of Different Types of Reactors

Properties	PWR	CANDU	PBMR
Reference capacity	1GWe	600-900 GWe	160 GWe
Enrichment ratio (%)	4.5	0.72	9
Fuel burnup (MWd/kgU)	45	7.5	90
Fuel unit	Assembly	Calandria	Pebble
Fuel unit dimension	21.4*21.4*400	10cm(d)*50cm	6 cm
Fuel unit volume (cm3)	183134	3926.99	113.097
Fuel unit mass	619.19 kg [Westinghouse]	24 kg	210g
UO2 mass in a single fuel unit	**480 kg** [a]	**22kg**	**9 g**
Number of fuel units in the core	193	4,560 [b]	456,000
UO_2 in the core (metric tons)	69.5 (950MWe)	84.7 (713MWe)	4.1
Refueling period	Cycle length	1.98 channels/day [c]	371.55 pebbles/day
Fuel residence time	12-18 months	12-18 months	3 years (6 passes)
U isotopes quantity per fuel unit	423.09 (kg)	19.39 (kg)	7.93 (g)
U-235 quantity in fuel unit	16.92 (kg)	0.14 (kg)	0.714 (g)
Total number of fuel units required for 1 SQ [d]	4.43 (=75kg/16.92kg)	535.7	105042
Estimated period to get 1 SQ	Per cycle	22.60 days (=535.7/23.76)	282.71 days (=105042/371.55)

Notes
[a] 0.0815 fraction of fuel unit mass was assumed.
[b] 12 (calandria/tube) x 380 (pressure tubes/reactor)
[c] 1.98 (channels/day) x12 (calandria/channel) =23.76 calandrias/day
[d] However, if losses during uranium conversion and losses during enrichment through tails assay are considered, the required fuel mass would be higher than these suggested values.

H.2 Estimate on the number of fuel assembly required to obtain 1 SQ of U-235 from PWR

A. General

Steps	Description
Step 1	**Quantity of U isotopes in UO2** $\frac{M(UO_2)}{M(U)} = \frac{235 \text{ x } (e) + 238 \text{ x } (1-e) + 16 \text{ x } 2}{235 \text{ x } (e) + 238 \text{ x } (1-e)}$ where 'e' is the U-235 enrichment ratio of fuels
Step 2	**Quantity of U-235 in uranium isotopes** $M(U-235) = M(UO_2) \text{ x } \frac{M(U)}{M(UO_2)} \text{ x } (e)$
Step 3	**Calculation of quantity of fuel assembly required for 1 SQ of U-235** $\text{No. of Fuel Assembly} = \frac{75 \text{ kg}}{M(U-235)}$

B: Example in case of PWRs (4% U-235 enrichment ratio assembly)

Steps	Description
Step 1	$\frac{M(UO_2)}{M(U)} = \frac{235 \text{ x } 0.04 + 238 \text{ x } 0.96 + 16 * 2}{235 \text{ x } 0.04 + 238 \text{ x } 0.96} = 1.1345$
Step 2	$M(U-235) = M(UO_2) \text{ x } \frac{M(U)}{M(UO_2)} \text{ x } (e) = M(UO_2) \text{ x } \frac{0.04}{1.1345} = M(UO2) \text{ x } 0.0353$
Step 3	From the table above, M (UO2) is 480 kg in PWR. M (U-235) = (480 kg) x (0.0353) =16.944 (kg). If we calculate 1 SQ of U-235 dividing 75 kg by 16.944 kg, 4.43 fuel assemblies are obtained. **Thus, 4.43 fuel assemblies are required for obtaining 1 SQ of U-235.**

APPENDIX I: EXPERT OPINION QUESTIONNAIRE

I.1 Lists of Questionnaire

Category	Assumed Capacity	Questionnaire
Off-design operation for HEU production at declared GCEP	200,000 kgSWU/yr	If there are 100 identical, different GCEPs that are trying to produce HEU each of the in aforementioned four ways (batch recycling, reconfiguration, add-on of modular cascades, connection of cascades), typically how many facilities will be detected out of 100 identical GCEPs for each?
Excess LEU production at declared GCEP		If there are 100 GCEPs that are trying to produce excess LEU in aforementioned three ways, typically how many facilities will be detected out of 100 identical GCEPs?
Clandestine GCEP operation	5-7,000kg SWU/yr	Typically, how many GCEPs would be detected by WAES and DIAL out of 100 clandestine GCEPs? (at short and large distances, respectively)
NU / LEU conversion at declared UCF	100 MT yellow cake/yr	If there are 100 identical, different UCFs that are trying to convert additional one SQ of NU, typically how many facilities will be detected out of 100 identical UCFs?
Clandestine UCF operation	100 MT yellow cake/yr	Typically, how many UCFs would be detected by WAES and Raman-based LIDAR out of 100 clandestine GCEPs? (at short and large distances, respectively)
LEU diversion from declared FFPs	500 MTU/yr	Typically, if there were or are 100 times identical, different attempts of diverting about 1000 kg of 3.5% enriched uranium (this corresponds to around 1 significant quantity) over one year from declared nuclear facilities, how many uranium diversion attempts would be typically detected?
LEU diversion from declared LWRs	1000 MWe	
NUF6 diversion from declared UCFs	100 MT yellow cake/yr	Typically, if there were or are 100 times identical, different attempts of diverting about 10 MT of UF6 from declared nuclear facilities, how many uranium diversion attempts would be typically detected?
LEUF6 / NUF6 diversion from declared GCEPs	500,000 [SWU/yr]	Typically, if there were or are 100 times identical, different attempts of diverting about 1 SQ over a year from declared GCEPs, how many uranium diversion attempts would be typically detected?
Illicit acquisition of nuclear material	1 SQ/yr	Typically, how many interstate illicit nuclear trade attempts for acquiring 1 SQ of nuclear material would be detected out of 100 occurring per year for each time period below?
		Typically, how many nuclear smuggling attempts for acquiring 1 SQ of nuclear material would be detected out of 100 occurring per year for each time period below?

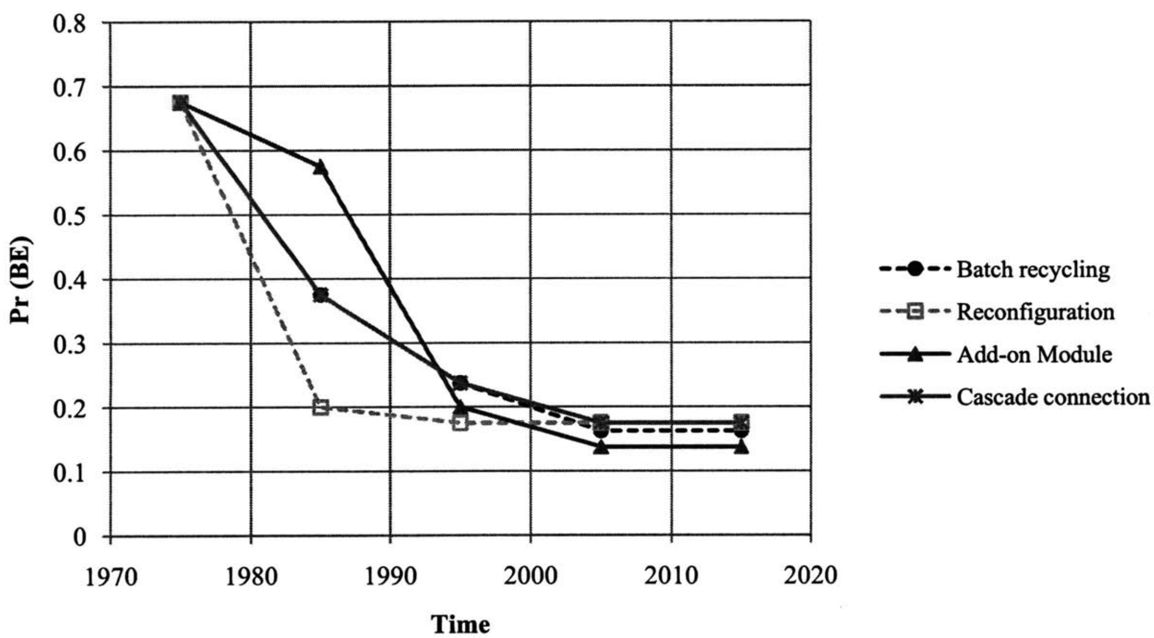
Note: GCEP (Gas Centrifuge Enrichment Plant), UCF(Uranium Conversion Facility), LWR(Light Water Reactor), FFP (Fuel Fabrication Plant)

I.2 Sample Table for Evaluation

Time period	Main feature of safeguards	LEU diversion from LWR	LEU diversion from FFP
1970s	Early stage of INFCIRC/153		
1980s	Matured stage of INFCIRC/153		
1990s	Early stage of Additional Protocol		
2000s	Matured stage of Additional Protocol		
2010s	Integrated safeguards system		

I.3 Translation of Expert Evaluation into Input Values

a. Detection Probability of Off-Design Operation Mode for HEU Production (in Type A countries)

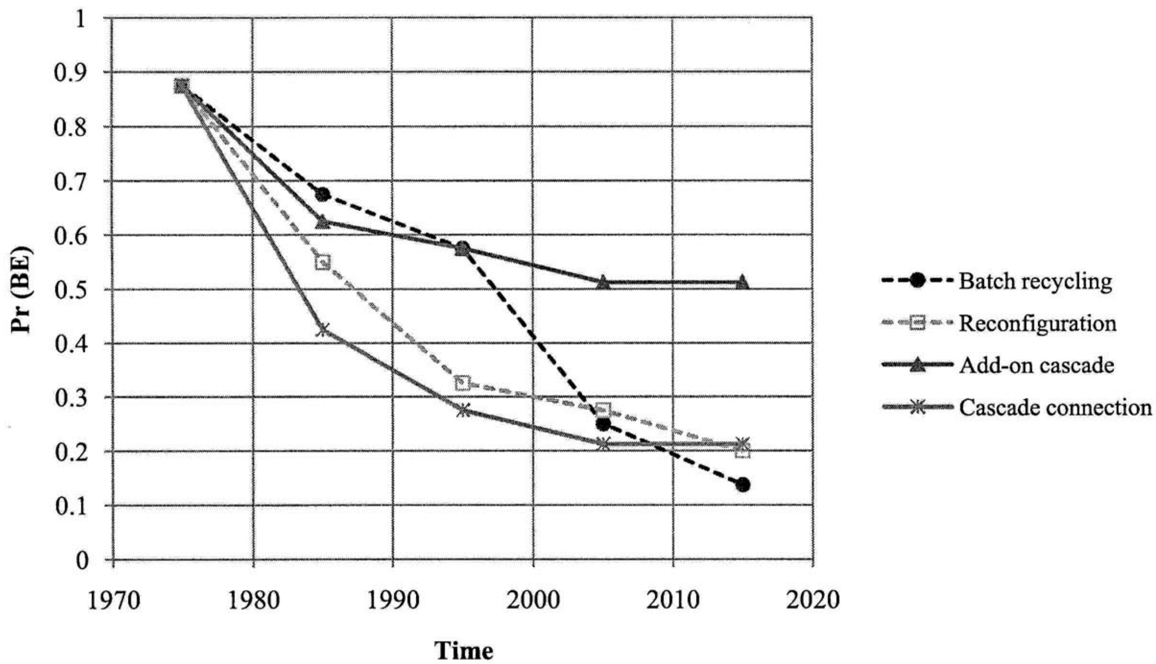


Notes

[a] Experts assumed that the add-on modular cascades are located on the site, but not within the declared cascades halls.

[b] Capacity of GCEP was assumed to be 200,000 kgSWU/yr.

b. Detection Probability of Off-Design Operation Mode for HEU Production (in Type B countries)



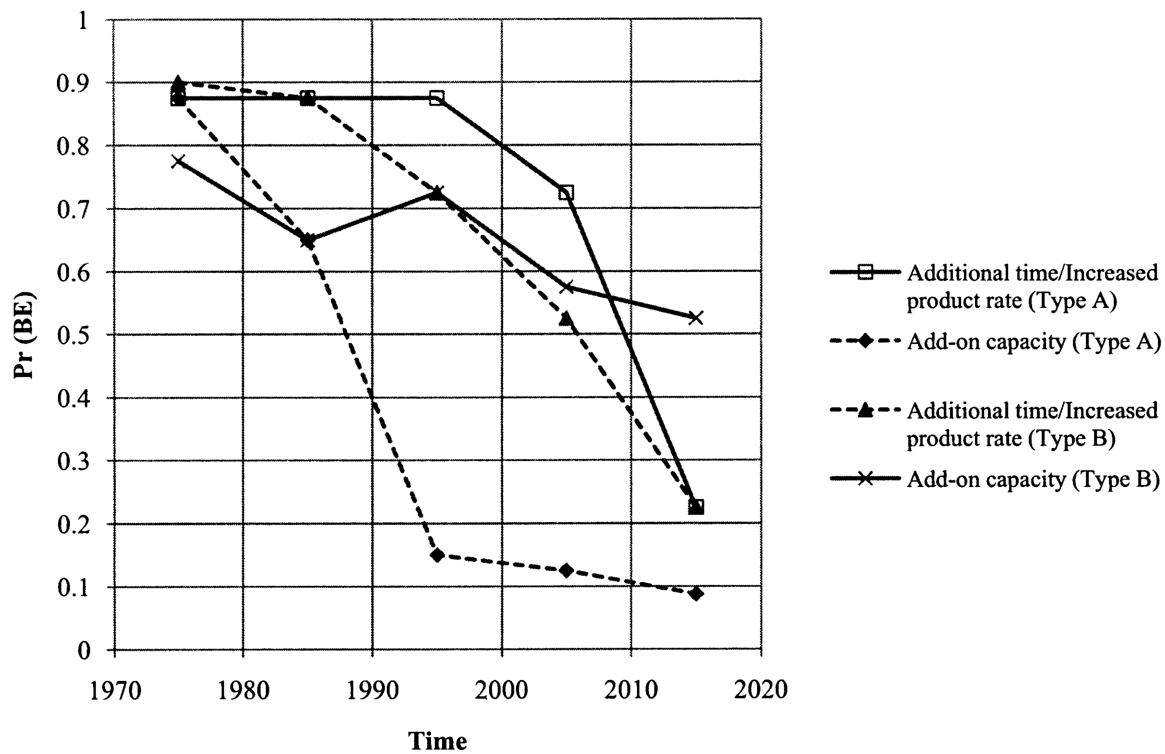
Notes

[a] Experts assumed that the add-on modular cascades are located on the site, but not within the declared cascades halls

[b] Assumed capacity : 200,000 kgSWU/yr

[c] A probability value for off-design operation with add-on cascade remains high in the 2010s without the AP in force.

c. Detection Probability of Excess LEU Production at Declared GCEPs



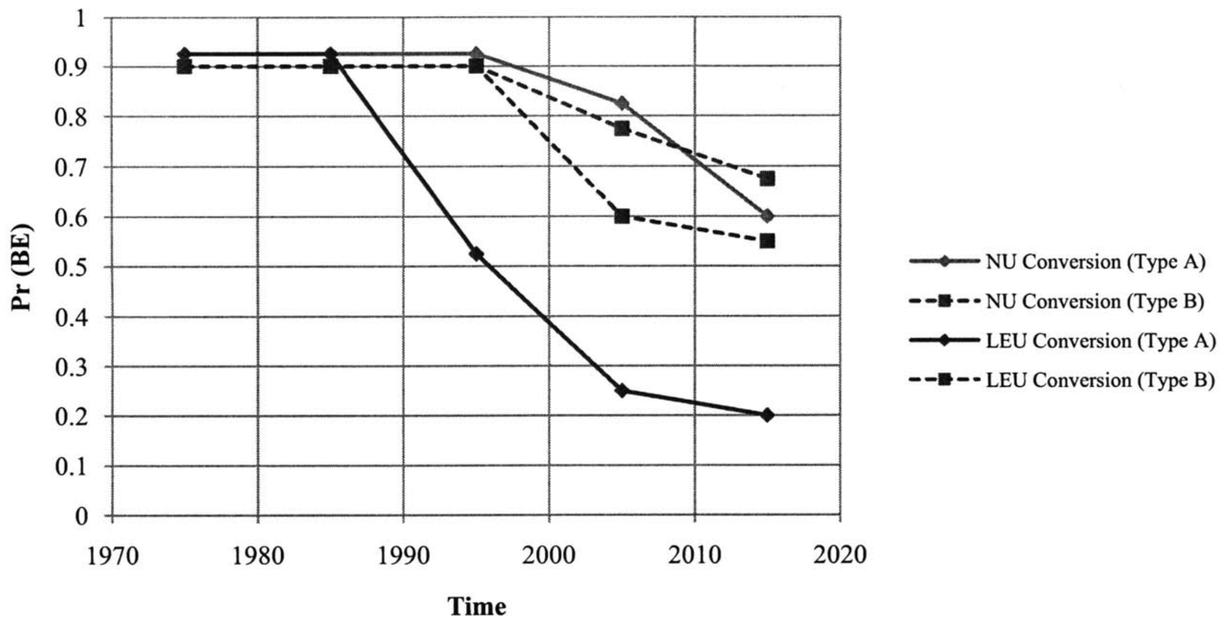
Notes

[a] Values depend on inspection measures and effort applied. For example, SNRI + mailbox could achieve 50% of detection goals set by the IAEA, whereas continuous monitoring at Feed/Product/Tails stations could achieve 90%.

[b] Experts assumed that the add-on modular cascades are located on the site, but not within the declared cascades halls. Considering the fact that IAEA inspectors shall have access only to the strategic points specified in the Subsidiary Arrangements within the declared facilities, proliferators' success probability for performing the add-on capacity operation is still high. [Paragraph 76 INFCIRC/153]

[c] There is an increase in the value of 'add-on capacity' operation for Type B countries. This is because an expert thinks that in the 80's the number of GCEPS and the amount of technology was smaller and less mature. However, the technology spread and INFCIRC 153 safeguards was behind the curve in the 90's until the AP came in force.

d. Detection of undeclared feed conversion at declared uranium conversion facilities.



Notes

[a] Assumed capacity: 100MT of Yellow cake/yr

[b] Values depend on inspection measures and effort applied. For example, SNRI + mailbox could achieve 50% of detection goals set by the IAEA, whereas extensive installed instrumentation (continuous monitoring) at Feed/Product/Tails stations could achieve 90%.

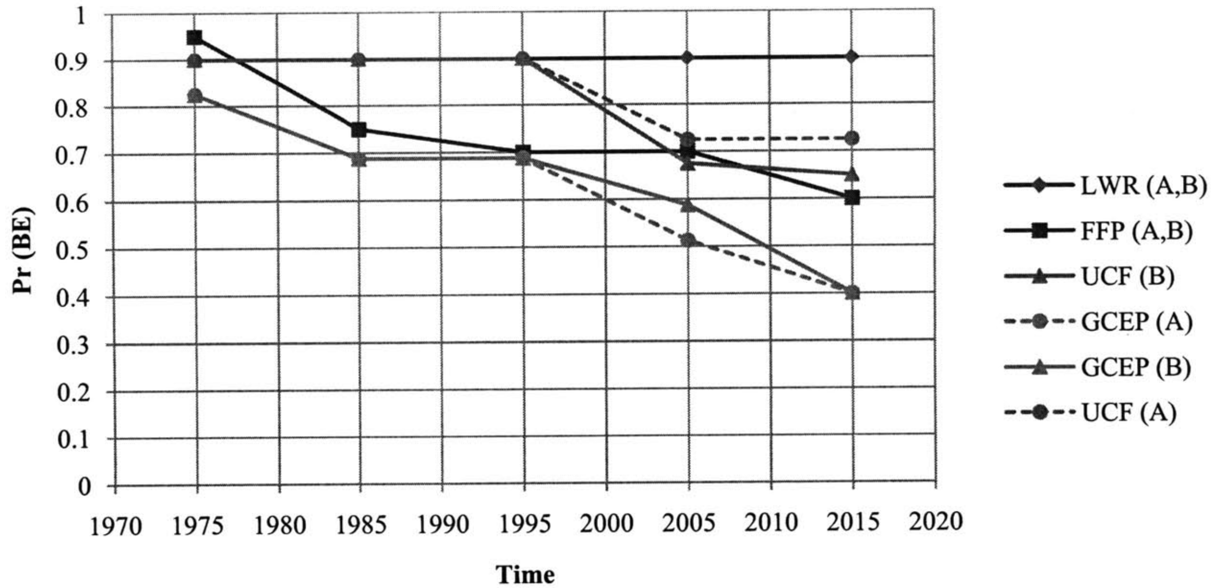
[c] Experts assumed that the add-on modular cascades are located on the site, but not within the declared cascades halls

[d] Type A countries have a higher success probability of processing NU. On the contrary, Type B countries have a higher success probability of processing LEU.

[e] Introduction of environmental sampling decreased the proliferator success probability.

[f] Enhanced access right under the AP is the factor that affected lower success probability for LEU conversion in Type A states. However, Type A states have better skill and technology to convert additional, undeclared NU without being detected.

e. Detection of uranium diversion from declared nuclear facilities



Throughput assumed for each facility

Facility Type	Throughput
LWR (Light Water Reactors)	1000 MWe
UCF (Uranium Conversion Facility)	100 MTU Yellow cake/yr
FFP (Fuel Fabrication Plant)	500 MTU/yr
GCEP (Gas Centrifuge Enrichment Plant)	500,000 kgSWU/yr

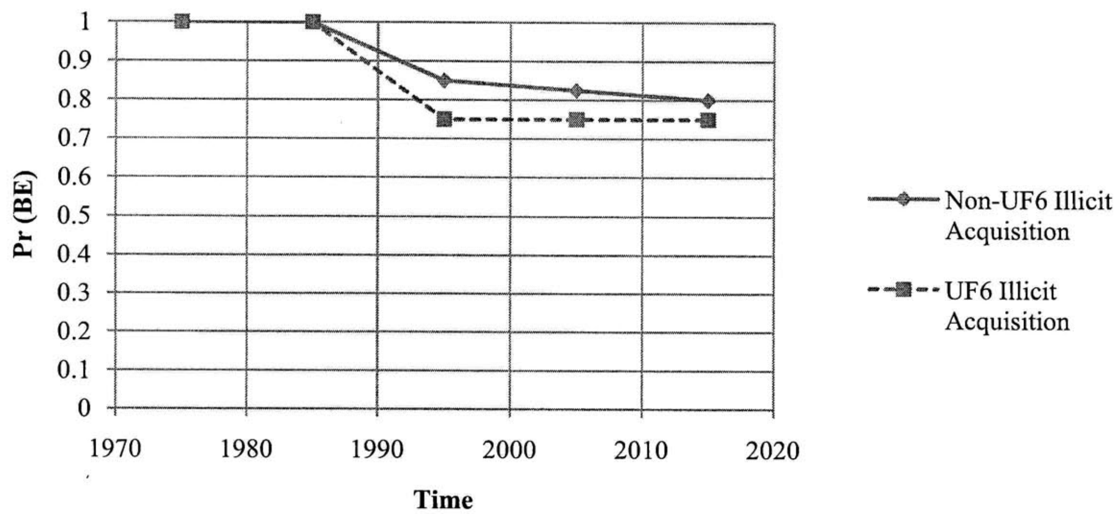
Experts stated that the IAEA still lacks the following resources:

[a] at LWRs: a method for detecting partial defects in fresh fuel and spent fuel in LWRs.

[b] at GCEPs: a method for verifying empty cylinder weights at enrichment plant (if there is no resident inspector and no continuously recording authenticated load cells)

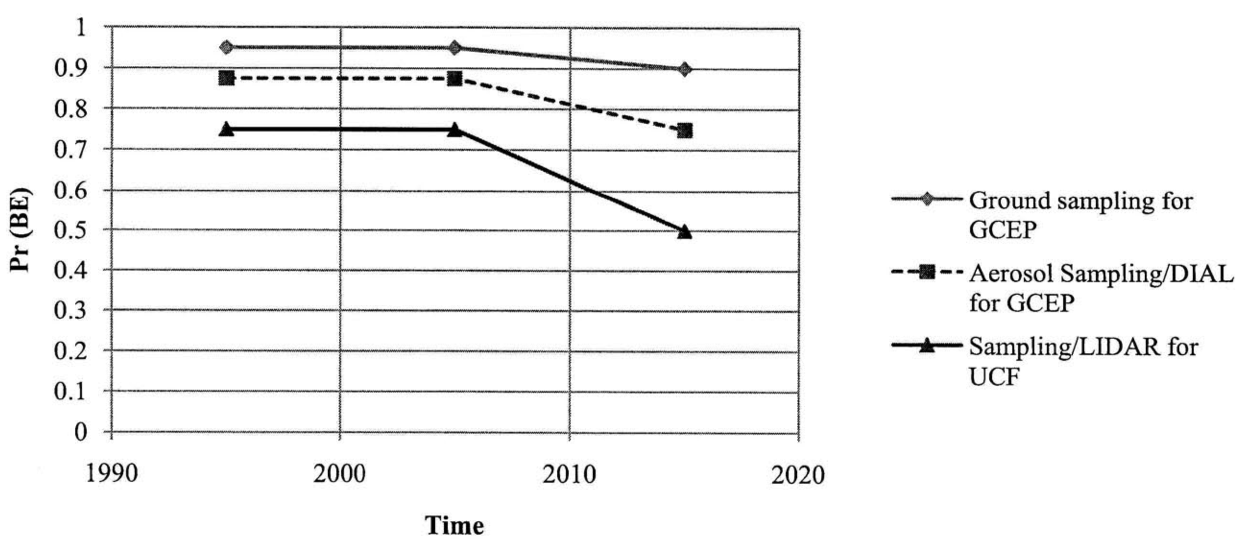
[c] at FFPs: a method to verify NMA because of the short residence time of produced fuel assemblies. This is because the operators want to move the assemblies out as quickly as possible for economic reasons.

f. Detection Probability of Illicit Acquisition of Nuclear Material



Notes
[a] Success probabilities for illicitly acquitting nuclear material will remain high in the 2010s.
[b] Nuclear material in the form of UF6 can be more easily detected than non-UF6 from of nuclear material.

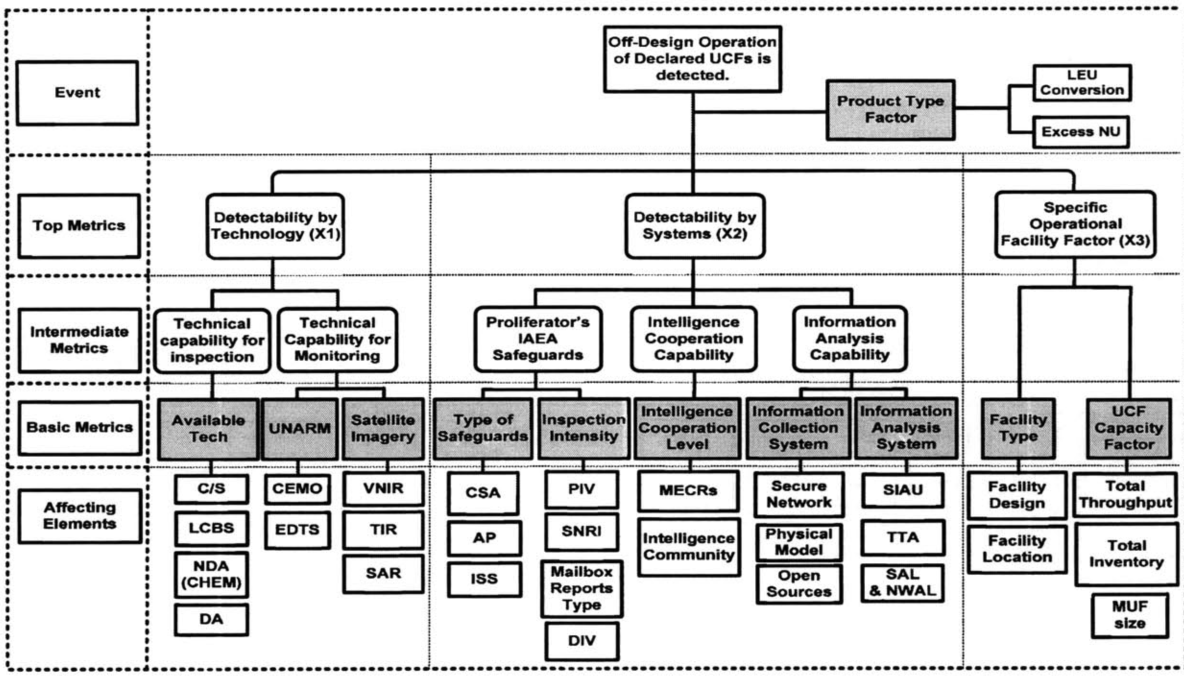
g. Detection probability of clandestine GCEPs and UCFs using ESWA and DIAL/LIDAR at short distances



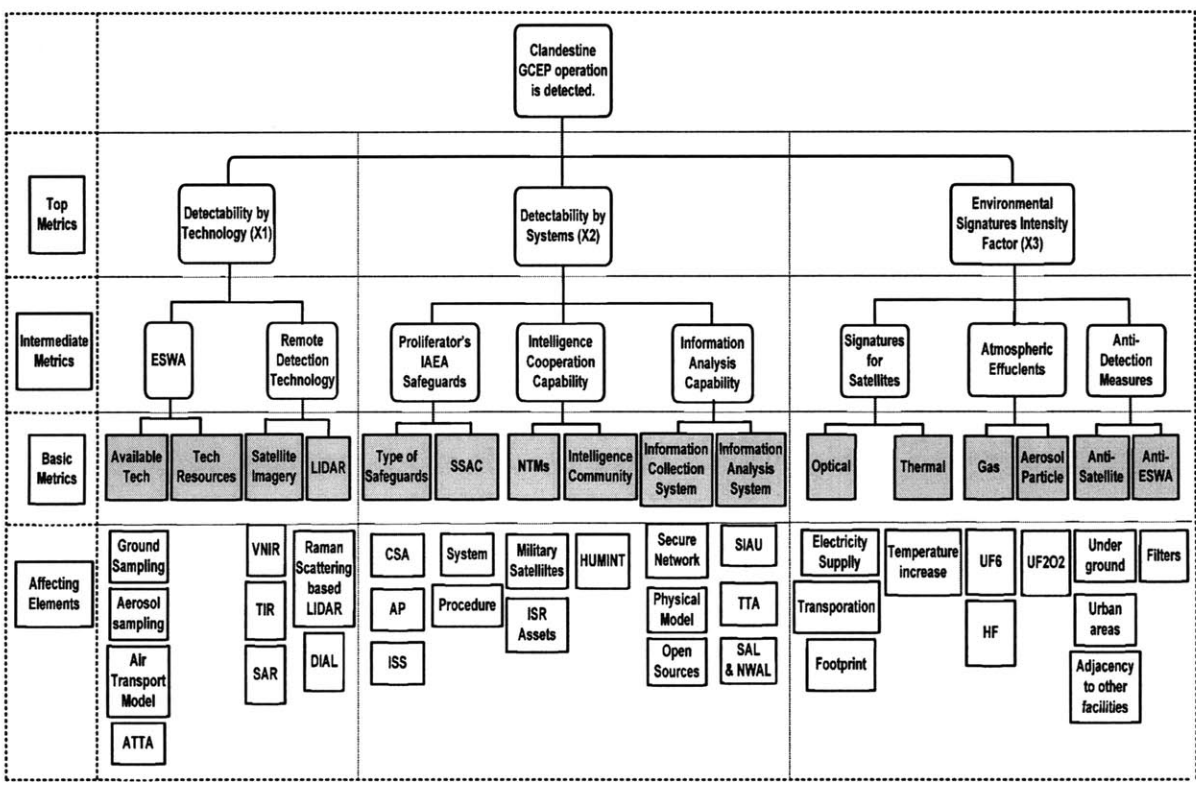
Note: The expert made the following assumptions in providing his evaluations:
[a] Constant monitoring over extended time.
[b] Bad retention technology for both cases A and B.
[c] The detections in the 5 km range will all be made just outside the fence.

APPENDIX J: HIERARCHIC METRICS

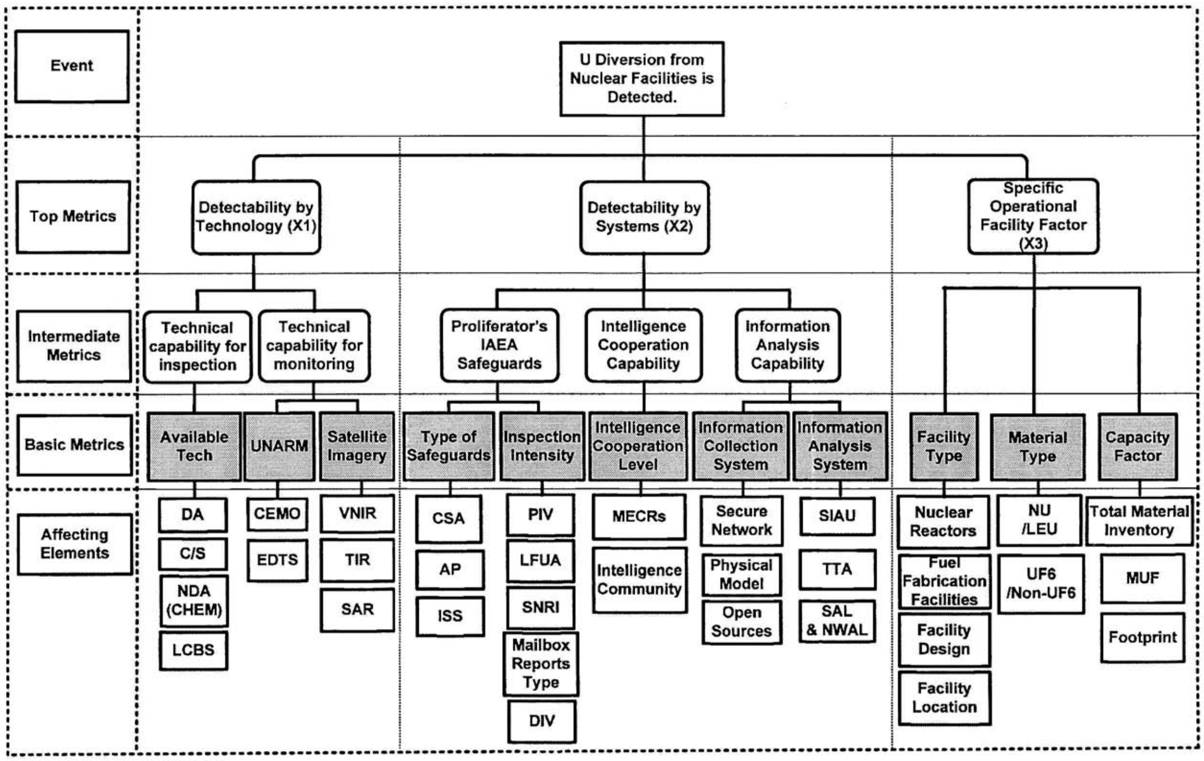
J.1 Hierarchic Metric for Detection of Off-Design Operation of UCFs



J.2 Hierarchic Metric for Detection of Clandestine Operation of GCEPs



J.3 Hierarchic Metric for Detection of Uranium Diversion



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