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The Safeguards Options Study

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DISCLAIMER

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This report represents the work of many different individuals in ten different organizations.

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EXECUTIVE SUMMARY

The Safeguards Options Study was initiated to aid the International Safeguards Division (ISD) of the DOE Office of Arms Control and Nonproliferation in developing its programs in enhanced international safeguards. The goal is to provide a technical basis for the ISD program in this area.

Limitations in the present approach to international safeguards, exemplified by the Iraq experience, provide much of the motivation for the Safeguards Options Study. Iraq was able to develop a significant nuclear weapons program while appearing to remain in full compliance with their responsibilities under the Nuclear Nonproliferation Treaty (NPT) at their declared facilities. This is in large measure because NPT safeguards were only applied at declared sites. The Iraqi weapons program was conducted at undeclared sites outside of traditional safeguards. Even at declared sites, traditional international safeguards only allow inspection activities at specific locations in a facility that are defined by previous agreement. In addition to these two limitations, there is a general feeling that changes will be required to cope with the increasing burden on the system resulting from the continued expansion and technical advancement of the world's nuclear facilities. Although a primary thrust of the study is to aid the International Atomic Energy Agency in both strengthening traditional safeguards and developing enhanced safeguards, it has also considered other international safeguards regimes. These include the support for regional arrangements such as the Argentine–Brazilian safeguards agreement, possible safeguards in weapons states, and technical cooperation programs such as those between the US and the states of the former Soviet Union.

Because of the desire to share the results of this study with appropriate members of the international nonproliferation community, emphasis has been placed on unclassified information and technologies that could be widely shared. From the start, the study members have been cognizant of the large amount of past and present work in this area. Therefore, there has been a great effort to avoid duplication of this work. For this reason most of the effort has concentrated on collecting this previous work and then developing practical options based on this information.

The study has produced several products. The first is a methodology for the development of options for enhanced international safeguards. Based on this methodology, a preliminary series of technical options were developed that can be used as a basis for detailed technical projects. Finally, a methodology, based on the options methodology, was developed for the evaluation of proposed projects.

The options methodology is based on the identification of a number of proliferation pathways. These are the various steps that a potential proliferant might have to master to develop a nuclear weapons capability. The pathways identified were source material acquisition; fuel fabrication; reactors, accelerators, and fuel in storage; reprocessing; enrichment; and weaponization. The report describes the place of each pathway in the proliferation process, the technology involved, the current status of international safeguards, and the signatures and indicators of proliferation associated with its pathway.

The development of safeguards options begins by defining a series of objectives for each individual pathway. Defined objectives assist us in understanding the safeguards needs required to obtain the objective. Finally, safeguards options, which are technical means of fulfilling the safeguards needs, are developed.

Options lists provided here should not be considered exhaustive, but provide a starting point to motivate technical proposals. Technological advances continually provide new options that might fulfill identified needs. Thus, researchers and project managers using this work to develop or review technical proposals should also consider new options that could fulfill the identified needs.

Options identified in this work are not ranked here because new technical options are continually evolving and because such rankings strongly depend on policy decisions. For example, environmental monitoring is technically feasible, but it can be very expensive and could have adverse political consequences with respect to cooperation between states. On the other hand, information management systems may be less objectionable politically, but they also may not be as effective in detecting clandestine operations. Prioritization of options and evaluation of projects also depends strongly on information provided in technical proposals. This provides a basis for generating technical proposals relevant to advanced safeguards and for evaluating those proposals.

Although the options developed are quite varied, Table I lists several options that are common to many pathways. One of these is the need to develop methods of finding undeclared sites. As discussed earlier, this is a major failing of current international safeguards, but it is also recognized that this is a very difficult problem. Among the suggested ways of addressing this problem are environmental monitoring and examining the use of commercially available satellite information. Another area that was emphasized is the requirement to augment the training of international inspectors and provide them with new procedures to handle the more taxing inspections contemplated under enhanced safeguards regimes. The role of modern information management systems both in the field and at the inspection headquarters was also recognized. These systems would handle not only inspection-related data but also other forms of open source literature that could be used to direct inspections and detect potential proliferation activities. Finally, it was recognized that there was room for improvement in more traditional forms of international safeguards. This included instrumentation to improve material measurements and improved containment/surveillance technology. An interesting part of the latter area is the use of remotely monitored instruments.

The evaluation methodology provides a means of setting priorities among projects as well as an explanation of the project ranking. It should be emphasized that only technical options are presented here. It is strongly based on the degree to which proposed projects will help in meeting the safeguards objectives developed in this study.

TABLE I. Options Appearing in Multiple Pathways

Option 1	Study the use of commercial satellites for detection of undeclared sites
Option 2	Develop a data system for use by inspectors in the field
Option 3	Expand inspector training to include information on potential proliferation signatures and indicators
Option 4	Develop uranium and plutonium analysis systems that can be used in the field
Option 5	Develop procedures and appropriate training for environmental monitoring
Option 6	Develop proliferation-related information management systems
Option 7	Improve the capability to verify design information at complex facilities
Option 8	Improve tags and seals for safeguards purposes
Option 9	Study ways to authenticate information from facility control systems
Option 10	Develop unattended monitoring equipment for use in bulk processing facilities
Option 11	Develop procedures for use during non-routine inspections

GLOSSARY

ADU	ammonium diurante
AVLIS	atomic vapor laser isotope separation
BWC	Biological Weapons Convention
BWR	boiling-water reactors
CANDU	heavy-water-moderated, natural-uranium (CANadian Deuterium Uranium) reactor
CHEMEX	chemical exchange
C-o-K	continuity-of-knowledge
C/S	containment and surveillance
CWC	Chemical Weapons Convention
DIAMO	Czech Uranium Industry
DIS	digital image surveillance
effective kilogram	a special unit used in safeguarding nuclear material (see footnote on p. 18)
EMIS	electromagnetic isotope separation
fertile	material that can be converted to fissile material when bombarded by neutrons
fissile	material (isotopes) that fissions when bombarded by thermal neutrons
GWe	GigaWatts of electrical power
HEU	high-enriched uranium
IAEA	International Atomic Energy Agency
ICPMS	inductively-coupled-plasma mass spectrometry
ISD	International Safeguards Division
LASCAR	large-scale reprocessing
LEU	low-enriched uranium
LINAC	linear accelerator
LMFBR	liquid-metal fast breeder reactor
LWR	light-water reactor
MC&A	materials control and accounting
MLIS	molecular laser isotope separation
MOX	mixed-oxide fuel
MWt	MegaWatts of thermal power
NDA	nondestructive assay
NPT	Nuclear Nonproliferation Treaty
NRTA	near-real-time accountancy
PWR	pressurized-water reactors
REO	rare earth oxide
significant quantity	enough nuclear material to make an explosive, taking into account losses expected in converting the material from its diverted form to a nuclear explosive
SNM	special nuclear material
SWU	separative work units
TBP	tributyl phosphate
TID	tamper indicating devices
UNSCOM	United Nations Special Commission

CONTENTS

THE SAFEGUARDS OPTIONS STUDY

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ABSTRACT

This Safeguards Options Study was initiated to aid the International Safeguards Division (ISD) of the DOE Office of Arms Control and Nonproliferation in developing its programs in enhanced international safeguards. The goal is to provide a technical basis for the ISD program in this area.

CHAPTER 1

INTRODUCTION

The Safeguards Options Study was initiated to aid the International Safeguards Division (ISD) of the DOE Office of Arms Control and Nonproliferation in developing its programs in enhanced international safeguards. The goal was to provide a technical basis for the ISD program in this area. The Safeguards Options Study has been a cooperative effort among ten organizations. These are Argonne National Laboratory, Brookhaven National Laboratory, Idaho National Engineering Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Mound Laboratory, Oak Ridge National Laboratory, Pacific Northwest Laboratories, Sandia National Laboratories, and Special Technologies Laboratory.

Much of the motivation for the Safeguards Options Study is the recognition after the Iraq experience that there are deficiencies in the present approach to international safeguards. While under International Atomic Energy Agency (IAEA) safeguards at their declared facilities, Iraq was able to develop a significant weapons program without being noticed. This is because negotiated safeguards only applied at declared sites. Even so, their nuclear weapons program clearly conflicted with Iraq's obligations under the Nuclear Nonproliferation Treaty (NPT) as a nonnuclear weapon state.

The Iraqi weapons program was conducted at undeclared sites outside of traditional safeguards. Even at declared sites traditional international safeguards were only exercised at specific locations in a facility that are defined by previous agreement. In addition to these two deficiencies, there is a general feeling that changes will be required to cope with the increasing burden on the system resulting from the continued expansion of world nuclear facilities. Although a primary thrust of the study has been to aid the IAEA in strengthening both traditional and enhanced safeguards, it has also considered other international safeguards regimes. These include the United Nations Special Commission (UNSCOM) effort in Iraq, support for regional arrangements such as the Argentine–Brazil bilateral safeguards agreement, possible safeguards in weapons states, and technical cooperation programs such as those between the US and the states of the former Soviet Union.

Because of the desire to share the results of this study with appropriate parts of the international nonproliferation community, emphasis has been placed on unclassified information and technologies that could be widely shared. From the start, the study members have been cognizant of the large amount of past and present work in this area. Great effort has been made to avoid duplication of this work. For this reason most of the effort has concentrated on collecting this previous work and then developing practical options based on this information.

The study has produced several products and the organization is shown schematically in Fig. 1. Chapter 2 provides a general methodology to identify options that could be developed for enhanced international safeguards. Chapters 3–8 identify technical options for individual proliferation pathways using this methodology. The pathways analyzed are

- source material acquisition;
- conversion and fuel fabrication;
- reactors, accelerators, and fuel in storage;
- spent fuel reprocessing;
- uranium enrichment; and
- weaponization.

These pathways were selected based on a review of literature sources identified in Appendix A. Although this list is not exhaustive, it is representative of proliferation pathways. Chapter 9 identifies common options among these individual pathways. These chapters provide the policy and research community with a basis for identifying and developing detailed safeguards-related activities and R&D projects that will produce fieldable technologies for which there is a clear need. The final product of this report is an evaluation methodology. Chapter 10 provides a model for evaluating how effectively proposed projects will meet existing advanced safeguards needs. This evaluation methodology provides a tool for optimizing the return on support activities and R&D funds. We emphasize that this report only presents technical options. Before being acted upon, these must be examined in a broader light by the policy community.

The report begins by describing the two methodologies in greater detail. This will be followed with chapters that apply the methodologies on each of the proliferation pathways individually. These chapters describe the technology involved in each pathway identified; the probable signatures and indicators associated with the pathway; and the objectives, needs, and options developed for detecting each pathway. A summary chapter looks at all of the pathways together. This allows the recognition of any options that cut across more than one pathway. These options are of particular interest because projects based on them offer the possibility of greater efficiency by addressing multiple pathways. The report also contains four appendices. Appendix A is a bibliography of open literature sources in nonproliferation. Appendices B and C contain further details pertaining to source material. Appendix D contains information relating to the project evaluation methodology.

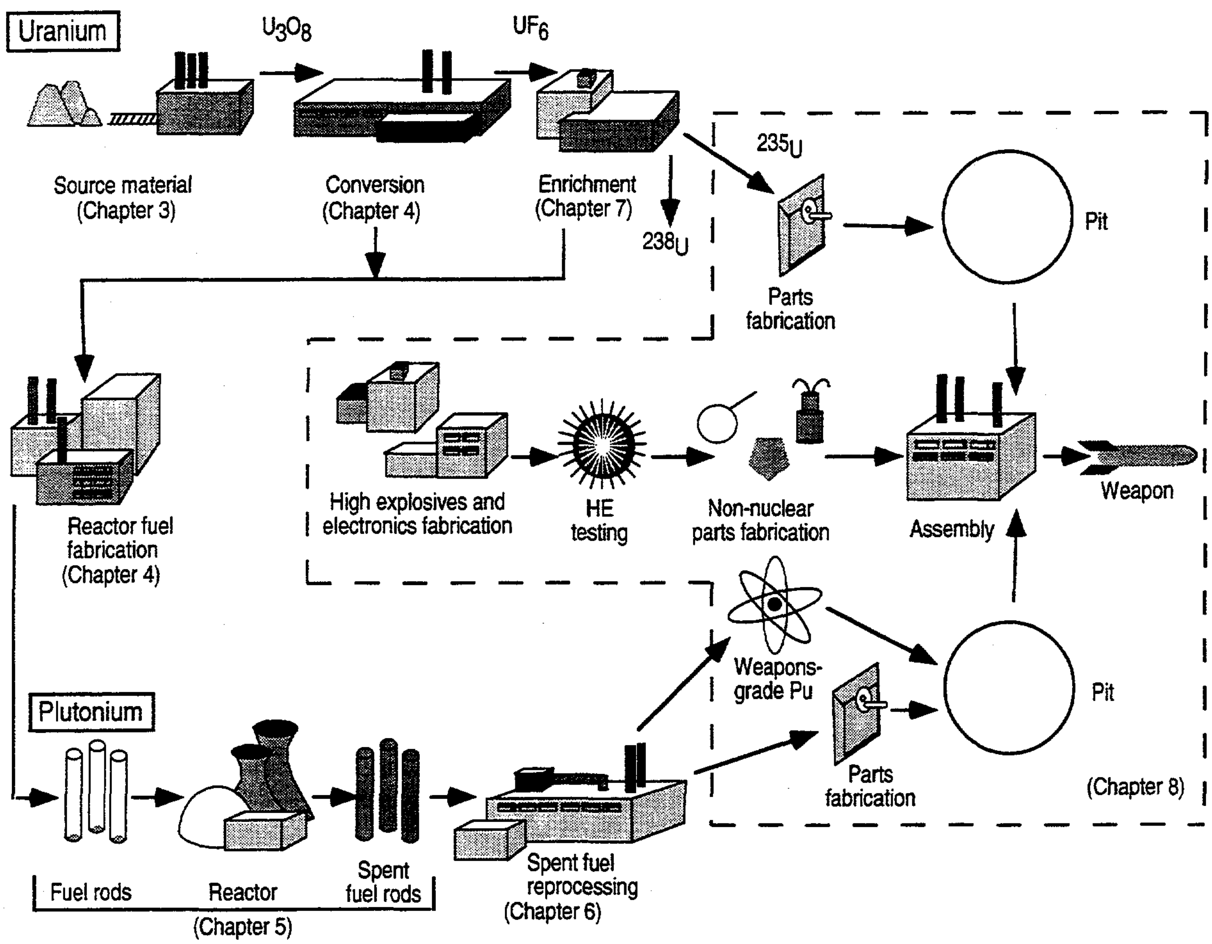

Fig. 1-1. Organization of chapters in this study.

CHAPTER 2

OPTIONS DEVELOPMENT METHODOLOGY

The development of options for enhanced safeguards used in this study is based on a series of steps that begin with the identification of the pathways or steps that a potential proliferant might follow to develop a nuclear weapons capability. Since World War II, a large number of studies have addressed this question. An annotated bibliography of open literature studies may be found in Appendix A of this report. The pathways identified during this study are source material acquisition, fuel fabrication, reactors and spent fuel, reprocessing, enrichment, and weaponization. Source material acquisition includes mining and milling of uranium and thorium-bearing ores. For this study, fuel fabrication includes the conversion of source material into a form suitable for use in an enrichment plant or reactor fuel elements for the production of plutonium. The reactor and spent fuel pathway includes the plutonium production reactor, possible production of plutonium with an accelerator, and storage of the spent fuel that could be reprocessed. The weaponization pathway covers not only construction of a weapon but also the necessary personnel development and R&D. Also included in the weaponization pathway is the development of the necessary military infrastructure (such as support facilities, delivery platforms, doctrine, and command and control) to make a weapon operational.

The next step is the statement of a series of general objectives of enhanced safeguards. These objectives are shown in Table 2-I.

TABLE 2-I. General Objectives of Enhanced Safeguards

- Detect diversion of materials at declared sites
- Detect misuse of facilities
- Detect undeclared nuclear activities at declared sites
- Detect undeclared nuclear activities at undeclared sites
- Develop transparency that demonstrates the absence of nuclear weapons-related work
- Strengthen state systems

Based on these general objectives, a series of specific objectives can be formulated for each pathway. These may be found in the section on each pathway: Chapters 3-8. The next step is to develop a needs list. The needs are designed to meet the individual advanced safeguards objectives for the pathways. The needs statements form an intermediate step in the development of options that could be pursued in enhancing safeguards. The options listed in this report can then be used as the basis of concrete proposals (projects) that can be prioritized using the evaluation methodology.

An example of this pathway-specific process can be taken from Chapter 6, Reprocessing.

One of the reprocessing objectives is to detect undeclared reprocessing.

This leads to a need: develop environmental monitoring methods to detect radioactive reprocessing signatures. An option to meet this need is to use environmental monitoring to detect radioactive reprocessing signatures.

In a similar way it is possible to develop a series of options that can form the basis for projects in each pathway. This step-by-step process has a number of advantages. Among the greatest is that consistent application of the methodology can suggest new options. Also, by examining how well options fulfill the needs and whether listed needs meet the objectives, it is possible to prevent "holes" in the coverage of safeguards objectives.

One other step is necessary in this methodology: integrate the options from the different pathways. This is done in Chapter 9, showing that many of the options will address needs associated with more than one pathway. Projects that can be developed from these common options will be given higher priority in the project evaluation process to optimize the return on investment.

CHAPTER 3

SOURCE MATERIAL ACQUISITION

Acquisition of nuclear source material is a possible first step of a nuclear proliferation scenario. However, development activity associated with production of nuclear source material within a non-nuclear state does not indicate an intention to develop or proliferate nuclear weapons. A regime may obtain nuclear source material from myriad origins. It is important to recognize that the acquisition of nuclear source materials need not coincide with the predominant methods that have been employed in the past. A regime whose intentions include the development and maintenance of a self-sufficient capability to obtain nuclear source material may elect to employ techniques that appear to be flawed both economically and practically (e.g., the recovery of uranium from complex low-grade ore, as a by-product of seawater desalination, or as a by-product of phosphoric acid and fertilizer production).

Source material denotes both material that contains fissile isotopes, which fission when bombarded by neutrons, and fertile isotopes, which are converted to fissile isotopes when bombarded with neutrons. These materials fall into the important chemical class known as the actinide group. The actinide group is composed of 15 elements with atomic numbers 89 to 103; the first four, which include thorium and uranium, are naturally occurring and the other eleven are man-made. Although a number of isotopes of the elements within this group are capable of supporting a chain reaction,[1] only thorium and uranium are considered as significant nuclear source materials for this study.

URANIUM

In most cases the development of an "in country" source for nuclear raw material will involve mining operations. The technologies associated with mining uranium deviate only slightly from those methods associated with conventional mineral mining operations.

Nuclear raw material may also be obtained by importing ore that is intended to be processed for the extraction of other minerals. However, the ore may also contain significant quantities of nuclear source material.

I. BACKGROUND

A. Pathway Description

Uranium is a heavy radioactive metal (19 times more dense than water) and is not as rare as was once believed. Widely distributed in the Earth's crust, uranium occurs to the extent of about 4 parts per million (ppm), making the element more plentiful than mercury, antimony, or silver. Uranium consists of three naturally occurring isotopes: ^{238}U (99.28%), ^{235}U (0.71%) and ^{234}U (0.005%). The isotope ^{235}U is a long-half-life nuclide that is fissionable when bombarded with thermal neutrons. As well as being the primary fuel source for nuclear reactors, small amounts of highly enriched uranium (HEU) (greater than 20% ^{235}U) can be the major ingredient of a nuclear explosive. Once obtained, HEU demonstrates advantages over other fissionable materials relative to its ease of fabrication and low toxicity.

The element uranium was first discovered in pitchblende, a massive variety of uraninite. The historical vein deposits at Jachymov in the Czech republic was one of the earliest sites mined for uranium. The mineralogy and occurrence of uranium are controlled by its geochemical behavior. The un-oxidized black ores are usually uraninite but may include bannerite, coffinite, or davidite. Vein deposits have been mined in Zaire, the Northwest Territories of Canada, Northern Australia, France, Colorado, New Mexico, Utah, and Alaska.

Geologists have theorized that in the oxygen-free atmosphere that existed two billion years ago, un-oxidized uraninite and bannerite grains accumulated as placer deposits in quartz-pebble conglomerates. Uranium resources of this type (which may also contain gold) are found in Canada, South Africa, and Brazil. This type of deposit may have been found in Venezuela with reported concentrations of up to 1% uranium.

When the uranium minerals are exposed to more oxidizing conditions near the Earth's surface, they are readily oxidized to a +6 valence state. In this state uranium is highly soluble and is mobilized in surface and ground water. Much of the oxidized uranium in solution ultimately reaches the oceans. Although the uranium in seawater amounts to only 0.002 ppm, it is selectively removed and incorporated in some marine phosphorite deposits, adsorbed by clay minerals, or included in the carbonate skeletons of organisms such as corals. Concentrations of marine phosphorites constitute a large uranium resource in the US, Africa, Brazil, and the Mediterranean region. In some parts of the world, these low-grade deposits are mined for their phosphate, which makes the recovery of the uranium feasible. Some lignites and marine black shale also contain enough uranium to warrant their consideration as a resource.

The first step in the production of uranium after mining is to crush and grind the ores to produce a coarse gravel-like material. The ground ores are then dissolved in leaching solutions of either acid or alkaline, depending on the additional constituents in the ores. The result of the leaching process furnishes either uranyl nitrate, uranyl sulphate, or uranyl carbonate. The uranyl salts are selectively removed from the leaching solution by ion exchange or solvent extraction with any of several organic solvents. In either case the uranium compound is physically removed from the original solution leaving many of the impurities behind. By repetition of the ion exchange or solvent extraction process, it is possible to obtain a pure uranium product. The uranium product next undergoes precipitation and drying and may be packaged in the form of a yellow cake. The yellow cake typically will be transported to an additional facility for further processing. The material may instead be further processed where the uranium is converted to uranium hexafluoride. This forms the basis for most uranium processes that include purification, concentration, and enrichment operations.

B. Proliferation Issues

At this time no international safeguards related to a state's internal development of nuclear source materials exist. Export and import of nuclear source material is under safeguards. However the possibility of importing or exporting ore with dual-use capability may circumvent the structure of the safeguards agreement. Significant advances have been made in uranium mine ventilation and radiation protection. Recent talks and meetings have been held in Russia and Iran with Chinese mining experts, related to uranium mining and production techniques.

The Czechoslovak Uranium Industry has changed its name to DIAMO and currently is in the process of re-orientation. DIAMO intends to become more involved as a supplier of fuel rods for nuclear power facilities and actively participate in radioactive waste disposal. They also intend to export uranium concentrate, and they are trying to reduce costs to offer advantageous marketing conditions.

C. Importance of the Pathway

Uranium has been extensively used as a fuel in nuclear reactors because of the availability of ^{235}U in natural or slightly enriched form. The health hazards associated with ^{235}U are minimal when compared to alternative nuclear fuel. In addition, a huge unclassified database is available within the scientific community that can support a regime developing nuclear source material capability.

D. Signatures and Indicators

Uranium is found combined with other elements in about 150 known minerals. In countries that currently process uranium, the mined material falls into three major categories.

- Ore, which has an economical concentration based upon processing costs and the world market value.
- Sub Ore, which is not economical to process under current market conditions.
- Waste, material with a very low concentration.

Because it is necessary to use low-grade ores, substantial and complex processing of these ores is required to obtain pure uranium. Mining facilities may pre-concentrate the ore using aboveground facilities that employ a process known as heap leaching. This process involves large piles of ore that are washed with either strong acid or alkalines to dissolve the uranium compounds.

Refining uses large quantities of strong solutions such as acids, base materials, and specialized solvents. The uranium refining process produces measurable signatures in the airborne and aqueous effluent from the refining facility. Water purification and de-ionization capabilities will be required to provide a large volume of product.

The pathway requires a large cargo system (trains, trucks) infrastructure to handle input materials in addition to large quantities of waste material that must be either stored or transported from the refining facility.

For the specific signatures associated with uranium mining processes, refer to Appendix B:

Table B-I. Exploration
Table B-II. Uranium Underground Mining
Table B-III. Uranium Surface Mining
Table B-IV. Uranium Milling: Alkaline Leach.

II. OBJECTIVES

Implementation of the following safeguards objectives will facilitate the timely and confident detection of the diversion of uranium from declared flows, or the undeclared production of uranium. These objectives are listed in Table 3-I.

The diversion or undeclared production of purified uranium is important because this can be the first step toward nuclear weaponization. Separated uranium can either be used as feed material in an enrichment plant to produce HEU or can be irradiated in a reactor for production of plutonium, either of which can be used in the production of nuclear weapons.

TABLE 3-I. Objectives for Safeguarding Uranium Source Material

Objective 1	Detect and monitor mining, concentration, milling, and refining of uranium source material at a declared site.
Objective 2	Detect and monitor mining, concentration, milling, and refining of uranium source material at an undeclared facility or an unknown site.
Objective 3	Detect and monitor the shipment of uranium-bearing ore to declared and undeclared regimes.
Objective 4	Detect and monitor production quantities of refined uranium at existing facilities.
Objective 5	Detect the development of new facilities for producing source material.

III. NEEDS

The needs addressing the foregoing objectives are listed in Table 3-II and are discussed below.

Needs 1 through 3 address the objectives of detecting and monitoring declared or undeclared mining activities at declared or unknown sites. An example of Need 1 would be detecting a large number of ventilation fans, which are necessary to remove the elevated radon gas associated with uranium ore.

Need 2 is best determined by knowledge of the geological attributes of the mining area. If low-grade ore is to be processed, a heap-leaching facility will probably be nearby.

In the case of heap leaching, large piles of ore must be placed on a membrane or material that is impervious to an acid or alkaline leaching solution. In the case of in-situ leaching, boreholes are drilled into the producing formation for injecting and recovering leaching solution.

Needs 4 through 6 may require physical samples of environmental material from near the mining operation. It is possible that effluent run-off may be detected in nearby creeks, rivers, or streams. These needs generally address the objectives of detecting and monitoring source material production where such production has not been declared.

Needs 7 and 8 are directed primarily at meeting Objectives 3 and 4, using signatures and other means to detect and monitor uranium product.

Needs 9 and 10 can address all of the identified objectives depending on how these needs are filled and what data sources are exploited.

TABLE 3-II. Needs for Safeguarding Uranium Source Material

Need 1	Detect the observable physical attributes associated with underground mining that may be used to determine that uranium ore is being extracted.
Need 2	Detect the observable physical attributes associated with surface mining that may be used to determine that uranium ore is being extracted.
Need 3	Observe the physical attributes associated with heap leaching and in-situ leaching of uranium ore that may be used for detection.
Need 4	Examine the chemical signatures associated with mining and leaching of uranium ore that may be used as a means of detection.
Need 5	Examine environmental and radiological signatures associated with mining and leaching of uranium ore that may be used as a means of detection.
Need 6	Observe the chemical and environmental signatures associated with uranium milling and refining that may be used as a means of detection.
Need 7	Observe and measure the physical output and the radiological signature from a suspect refining process to determine if uranium is the output material.
Need 8	Track shipments of materials and chemicals for the refining processes associated with uranium source material.
Need 9	Identify the technical disciplines of personnel associated with a suspect mining, milling or refining process. Determine if they are aligned with uranium source material production.
Need 10	Identify advanced information systems to provide data on mining, milling, and refining related to source materials.

IV. OPTIONS

The safeguards options are described, and the need related to the option is referred to by number. Some of the options overlap and provide assistance for more than one need. These options are listed in Table 3-III and discussed below.

Option 1: Develop safeguards use of "Spot," "LandSat," or other commercial satellite visual information capability

Addresses Needs 1, 2, 3

Developing the capability to interpret satellite imagery for safeguards purposes is essential to an expanding safeguards regime. This capability is useful for many aspects of detecting a potential proliferation scenario. The specific observables related to uranium mining include

- Large ore trucks associated with transportation of mine rock;
- Ore piles;

TABLE 3-III. Advanced Safeguards Options for Source Materials

Uranium

Instrumentation, Equipment, and Methods

Option 1	Develop safeguards use of "Spot," "LandSat," or other commercial satellites.
Option 2	Develop remote sensing and environmental monitoring for safeguards.
Option 3	Develop portable air-sampling equipment for short-term field acquisition.
Option 4	Develop small, fast-reaction, chemical uranium sensors.
Option 5	Develop environmental sampling procedures for suspect sites.
Option 6	Employ portable gamma-ray instrumentation for the analysis of uranium.

Training

Option 7	Provide inspectors with observational training to increase their awareness of techniques related to mining of nuclear source material.

Information Systems

Option 8	Develop advanced information systems that are accessible from the field.

Thorium

Instrumentation, Equipment, and Methods

Option 9	Develop instrumentation for detecting and monitoring thorium concentrations in plant product stream and in the plant waste stream.
Option 10	Develop instrumentation for detecting purified thorium or thorium compounds in sealed metal containers.
Option 11	Develop instrumentation for detecting the concentration of ^{233}U in a sealed metal container.

Training

Option 12	Provide observational training to inspectors.

Information Systems

Option 13	Develop advanced information systems related to the production of and world trade in thorium minerals and products and to the characteristics of suspect sites.

- A large number of ventilation fans, which are necessary to remove the radon associated with uranium mining operations;
- Large vapor plume;
- Water pumping from underground activities;
- Drilling and blasting;
- Heap leaching facilities;
- Tailing/sub-ore piles;
- Tailing ponds;
- Crushing equipment;
- Extraction equipment;
- Power lines;
- Effluent ponds;
- Large water purification/processing capabilities;
- Tanks for strong acid and base materials;
- Significant train and truck delivery of acids, bases, and solvent materials; and
- Large waste piles and transport activity removing large quantities of waste materials.

Option 2: Development of remote sensing capability for safeguards and environmental monitoring. This includes photographic or high-resolution TV capability

Addresses Needs 3, 4, 5, and 6

The development of a fixed wing or helicopter capability that facilitates remote sensing will greatly enhance the capability of the safeguards regime. Site characterization using laser fluorescence, ultraviolet (UV) and infra-red (IR) sensors, and photography will improve safeguards and furnish valuable environmental data. Site characterization capabilities could monitor

- Large ore trucks associated with transportation of mine rock;
- Ore piles;
- A large number of ventilation fans, which are necessary to remove the radon and radon daughters associated with uranium mining operations;
- Large IR signatures from ventilation fans, ore crushing/grinding machinery, milling/extraction processes, and effluent streams;
- Large vapor plume;
- Water pumping from underground activities;
- Drilling and blasting;
- Heap leaching facilities;

- Tailing/sub-ore piles;
- Tailing ponds;
- Crushing equipment;
- Extraction equipment;
- Power lines; and
- Fluorescence signatures from spilled chemicals or chemicals absorbed by surrounding trees and plants.

Option 3: Development of portable air sampling equipment for short-term field acquisition

Addresses Need 1

This equipment will allow sampling of the discharge air from underground ventilation fans. Analysis of the airborne effluent can detect chemical or radioactive species associated with uranium. Laboratory instruments that may be used for analysis include the following types:

- Mass spectrometry,
- Gamma-ray spectroscopy,
- Low-background alpha/beta particle counters, and
- Lidar and laser fluorescence.

Option 4: Develop small, hand-carried, fast-reaction chemical sensors.

Addresses Needs 3, 4, 5, and 6

Fast-acting sensors that chemically test for the presence of uranium, thorium, or other effluent signatures associated with uranium mining, concentration, or refining would be useful in field operations. These sensors could be employed either to locate unknown operations or to confirm undeclared operations at a suspect site. The sensor should be suitable for immersion into effluent streams or casual water.

Option 5: Develop environmental sampling procedures for suspect sites

Addresses Needs 4, 5, and 6

The procedures provide samples to be analyzed for chemical and radioactive species associated with uranium mining and milling. The analysis of various environmental samples is a developing technique that may be used to detect undeclared activities in all facets of a proliferation scenario. Laboratory instruments that may be used for analysis include the following types:

- Molecular spectroscopy,
- Chromatography,
- Electrophoresis,
- Gas-chromatograph mass spectroscopy, and
- Laboratory chemical analysis.

Option 6: Portable gamma-ray instrumentation for the analysis of uranium

Addresses Need 7.

Development of a small, portable gamma-ray instrument could analyze materials on-site.

Option 7: Observational training

Addresses Needs 1, 2, 3, and 9

Increasing the inspector's awareness of techniques related to mining procedures associated with nuclear source material will enhance the probability of early detection.

Option 8: Advanced information systems that are accessible from the field

Addresses Needs 8, 9, and 10

Information systems that employ neural network query capability are becoming the leading edge of computer technology. These systems will provide an unsophisticated user with unrivaled capability when conducting data searches and information matching. Development and deployment of these types of systems increases the reliability of the safeguards regime.

THORIUM

I. BACKGROUND

A. Pathway Description

When the naturally occurring fertile nuclide ^{232}Th captures a neutron, ^{233}Th is produced, which in turn decays via ^{233}Pa to ^{233}U in 27 days. One likely nuclear application is in a sodium-cooled fast reactor where thorium metal would capture a neutron and be converted to ^{233}U. However, in the case of the thorium fuel cycle, purified thorium dioxide (ThO_2) is preferred over thorium metal for use as reactor fuel for light-water, heavy-water, and liquid-metal fast-breeder reactors, due to rapid oxidation of thorium metal in a reactor environment.[2]

Thorium is currently produced primarily as a by-product of monazite mineral processing to obtain rare earths. Currently, the major monazite-producing countries are Australia, Brazil, China, India, Malaysia, the Republic of South Africa, Sri Lanka, Thailand and the United States. Thorium resources are also known to exist in Denmark (Greenland), Portugal, Egypt (Nile Delta), Korea, Iran, Liberia, Turkey, Kenya, Uganda, Nigeria, Sierra Leone, Argentina, Norway, Former Soviet Union, Uruguay, Malagasy Republic, Malawi, and Zaire.[2-5]

In some cases (e.g., in Canada), thorium is also obtained as a by-product of processing uranothorianite, $(U,Th)O_2$, ores for uranium.

Limited demand for thorium, relative to the rare earths, continues to create an extensive world oversupply of thorium compounds and residues. Excess thorium, not designated for commercial use, is either disposed of as a radioactive waste or stored for potential use as a nuclear fuel in the $^{232}Th/^{233}U$ fuel cycle or in other applications, such as alloys, electronics, gas mantles, welding, and chemical and medical uses. Currently, however, only a few foreign-based nuclear reactors operate with the $^{232}Th/^{233}U$ fuel cycle. Moreover, in the case of non-energy uses of thorium, the long-term outlook for demand is for a significant decline as the search for substitutes continues.[5,6]

B. Proliferation Issues

Irradiated thorium is the only known source of ^{233}U, which is a long-lived nuclide that will undergo fission with both fast and thermal neutrons. Furthermore, in thermal-neutron reactions, ^{233}U has an important advantage over ^{235}U or ^{239}Pu in that the number of neutrons produced per thermal neutron absorbed is higher for ^{233}U than for the other fissile nuclides. Moreover, ^{233}U could be used as a nuclear explosive if it has not been denatured by isotopic dilution with ^{238}U to form a mixture containing too little ^{233}U.[2] Production of a nuclear explosive from such a mixture would require costly and difficult isotope separation.

C. Relevant Technologies/Facilities

The technologies/facilities required to produce nuclear-grade thorium are associated with the following processes: mining, concentration, extraction, purification, and conversion. These processes and associated facilities, with respect to thorium, are discussed in detail in Appendix C. The technologies and facilities that have been used to separate ^{233}U from irradiated thorium and to produce a uranium product (mixture of UO_3 and U_3O_8) are described in detail by Rathvon, et al.[7] Technologies for producing pure uranium metal from these products are discussed in detail by Harrington and Ruehle.[8] Only the purification, conversion, and separation facilities are specific to the production of nuclear-grade thorium products and ^{233}U

product and hence would currently qualify as "Principal Nuclear Facilities" in the eyes of the IAEA, providing that more than one ***effective kilogram**** of thorium or uranium is commonly used.[9]

D. Importance of the Pathway

Thorium has not heretofore been extensively used in nuclear reactors because of the ready availability of ^{235}U in natural or slightly enriched uranium. Moreover, significant health hazards are associated with purified thorium that are not met with purified uranium. However, in areas where uranium is scarce and the conservation of neutrons and fissile material is of great importance, the production of ^{233}U from thorium becomes of greater significance, especially if these areas are also rich in thorium resources. For example, thorium contained in monazite mined from beach sands was India's only source of uranium before the uranium mines of Jaduguda opened.[10] Although India is currently developing its domestic uranium resources, thorium is the resource that India foresees as the long-term basis for its nuclear power program. They currently operate a thorium plant and a fast breeder test reactor.[11]

E. Signatures and Indicators

The following lists signatures or indicators or both for thorium mining, milling, extraction, purification, and conversion.

Mining and Milling: If concentrated monazite that contains thorium is present, radioactivity higher than normal background can be detected. In Australia, gamma-ray radiation levels in the mining parts of the operation range from 0.2 to 16 microSievert/hour** (μSv/h). In the "wet plant," gamma-ray dosages of up to 4 μSv/h have been noted. At the end of the monazite circuit in the "dry plant," levels up to 60 or 80 μSv/h were noted near a full monazite bag (2 tonnes) and up to 500 μSv/h between bags in monazite storage.[12] Effluent and wastes generated by a typical US heavy-mineral placer mining operation are shown in Appendix C, Table C-V.

Extraction: If a rare-earth plant is processing monazite, the presence of a thorium nitrate stream would be evident. This would be a waste stream unless purification of thorium is

* *"Effective kilogram"* is a special unit used in safeguarding *nuclear material*. In the case of thorium, the quantity in "effective kilograms" is obtained by taking the weight of thorium in kilograms multiplied by 0.00005. For uranium with an enrichment of 1% and above, its weight in kilograms is multiplied by the square of its enrichment. For uranium with an enrichment below 1% and above 0.5%, its weight in kilograms is multiplied by 0.0001.

** 100 rem = one Sievert.

planned. Effluent and wastes generated by a typical rare-earth/monazite processing operation in the US are shown in Appendix C, Table C-VI.

If a uranium extraction operation is also extracting thorium, the operation may be using alkyl phosphoric acid solvent such as EHPA, a primary amine such as Primene JM-T, or an organic phosphorus compound in their solvent extraction circuit for thorium.[13] If thorium is not present, or not being recovered, then this circuit would not be operating. Although tributyl phosphate (TBP) is also used to extract thorium,[2] the presence of an operating TBP solvent extraction circuit cannot in itself be considered as a signature for thorium because this circuit is also used to extract uranium. If thorium is present in the ore and it is not being recovered, it will be evident in the mill tailings.

<u>Purification</u>: The primary signatures for this operation would be the presence of TBP along with kerosene, Xylene, Solvesso 100, or Varsol, depending on the country/process involved, together with a thorium product consisting of thorium nitrate or crystals of hydrated thorium nitrate. This operation is normally only performed when thorium is to be used in a nuclear application.

<u>Conversion</u>: The primary signatures for the production of pure thorium metal are the production, purchase, and use of ThF_4, $ThCl_4$, or ThI_4.[2] Thorium would be in the form of purified ThO_2 for the production of reactor fuel or for the production of ThF_4 or $ThCl_4$.

F. Pathway Control

Currently, safeguards Agreements between the IAEA (the Agency) and non-nuclear-weapon states party to the NPT[9] are negotiated according to the following provisions:

1. Safeguards shall not apply to material in mining or ore processing activities (e.g., monazite, uranothorianite ores, and other ores containing the minerals listed in Table C-I of Appendix C).

2. When any material containing thorium that has not reached the stage of the nuclear fuel cycle is directly or indirectly exported to, or imported by, a non-nuclear-weapon state, the state shall inform the Agency of the material's quantity and composition, unless it is imported/exported for specifically non-nuclear purposes.

3. When any *nuclear material* * of a composition and purity suitable for fuel fabrication (e.g., purified ThO_2) leaves the plant or the process stage in which it has been produced, or when such nuclear material is imported into the state, the nuclear material shall become subject to the other safeguards procedures specified in the Agreement.

4. *Nuclear material* that would otherwise be subject to safeguards shall be exempt from safeguards **at the request of the state**, provided that *nuclear material* so exempted in the state **may not at any time exceed twenty metric tons of thorium.**

5. The Agency should be provided with information concerning the features of *facilities*** relevant to safeguarding *nuclear material* (e.g., facilities for purifying ThO_2 or producing and separating ^{233}U). Moreover, this design information should be re-examined in the light of changes in operating conditions.

6. *Facilities* and material balance areas outside *facilities* with a thorium content or annual throughput, whichever is greater, of *nuclear material* not exceeding five effective kilograms of thorium shall not be routinely inspected more than once a year. If more than five effective kilograms of thorium are involved, the frequency of inspection shall be determined in accordance with INFCIRC/153 (corrected), paragraph 80.[9]

Demonstrating the importance of monazite, both India and Brazil embargo its export because it is the principal ore of thorium. There is evidence of at least one attempt at clandestine traffic in thorium out of Brazil. Media reports out of Brazil† claimed that Brazilian authorities had confiscated 1300 kg of thorianite (a thorium-containing mineral) destined for Iraq. Reportedly, as of September 2, 1993, Brazil had not officially informed the IAEA of the find.[14]

Monazite is also currently a restricted export from Australia. Australia exports monazite to customers in France, the US, and Malaysia. Twice in the past, the Australian government has banned the export of monazite "to ensure adequate supplies of thorium to the Australian Atomic Energy Commission."[12]

* "Nuclear material" means any source or any special fissionable material as defined in Article XX of the Statute (reproduced in document INFCIRC/140). In this context, the source material shall not be interpreted as applying to ore or ore residue.

** "Facility" means a reactor, conversion plant, fabrication plant, critical facility, or any location where *nuclear material* in amounts greater than one *effective kilogram* is customarily used.

† Reported on Rio de Janeiro Rede Globo Television, in Portuguese, 1600 GMT, 18 Aug., 1993.

In France, Rhone-Poulenc SA was the leading producer of thorium compounds. Thorium was produced as a byproduct during processing for the rare earths at its operations in La Rochelle, France, and at Freeport, Texas. The products were derived almost entirely from monazite.[5]

The US exports thorium ore, monazite, and concentrate (destination not identified). US government stocks of thorium nitrate in the National Defense Stockpile in excess of 600 000 pounds were authorized for disposal.[5] Thorium nitrate from this stockpile was used as the starting material for preparing the thoria (ThO_2) feed material used in ^{233}U production at both Savannah River and Hanford.[7]

II. OBJECTIVES

Implementation of the safeguards objectives listed in Table 3-IV will facilitate the timely and confident detection of the diversion of thorium from declared plant flows or the undeclared production of nuclear-grade thorium products or the undeclared production of fissile ^{233}U or all of the above.

TABLE 3-IV. Objectives for Safeguarding Thorium Source Material

Objective 1	Detect and monitor mining, concentration, milling, and refining of uranium source material at a declared site.
Objective 1	Detect the diversion of imported/exported purified thorium products used in the production of reactor fuels or the diversion of pure thorium metal.
Objective 2	Detect clandestine irradiation of thorium for producing weapon-grade ^{233}U.
Objective 3	Detect the diversion of a significant quantity of thorium-containing material that has been declared imported/exported for specifically non-nuclear purposes.
Objective 4	Detect the production of excess undeclared purified thorium at a declared purification or conversion facility.
Objective 5	Detect the clandestine production of purified thorium products at undeclared facilities.

The diversion or undeclared production of purified thorium product is important because this material can be clandestinely included in a reactor fuel load, or otherwise irradiated, to produce fissile ^{233}U. This product can subsequently be chemically separated from the thorium and fission products in an undeclared facility to produce weapon-grade uranium with a potential for direct use in a nuclear weapon program.

III. NEEDS

The needs addressing the foregoing objectives are listed in Table 3-V and discussed below.

TABLE 3-V. Needs for Safeguarding Thorium Source Material

Need 1	Detect the observable physical attributes associated with underground mining that may be used to determine that uranium ore is being extracted.
Need 1	Detect and monitor the production of and world trade in ores containing the thorium minerals listed in Table C-I of Appendix C as well as concentrates and products produced from these minerals.
Need 2	Detect and monitor the thorium throughput at thorium extraction facilities, including rare earth oxide (REO) plants where thorium is detected, and monitor the disposition/distribution of the thorium product/by-product/waste generated.
Need 3	Detect the presence of purified thorium or thorium compounds in sealed metal containers, including fuel pins.
Need 4	Detect the presence of irradiated thorium and ^{233}U in sealed metal containers, including fuel pins, and determine the concentration of ^{233}U.
Need 5	Detect and monitor thorium throughput at thorium purification and conversion facilities, and at plants that produce non-nuclear products from thorium or thorium compounds.
Need 6	Sample the environment in and near thorium extraction facilities (including REO plants), purification facilities, conversion facilities, and plants that produce non-nuclear products from thorium or thorium compounds.
Need 7	Design verification procedures for operating facilities.
Need 8	Verify production capacity.
Need 9	Design advanced information systems providing and managing data related to suspect sites.
Need 10	Develop safeguards approaches for unconventional extraction, purification, and conversion technologies.

Needs 1 and 3 address the objective of detecting the diversion of imported or exported purified thorium products used in the production of reactor fuels or pure thorium metal, either of which can ultimately be converted to fissile ^{233}U. Development of advanced information systems with data related to the production of and world trade in products produced from the thorium minerals listed in Table C-I of Appendix C (Need 1) would assist in detecting a diversion of purified thorium products (ThO_2, ThF_4, $ThCl_4$, thorium nitrate, thorium metal) to an undeclared fuel fabrication facility. Development of a method for detecting the presence of purified thorium or thorium compounds in sealed metal containers (Need 3) would provide a means of assuring accountability and would further facilitate the tracking of this type of material to its ultimate destination.

Needs 3 and 4 address the objective of detecting the clandestine irradiation of thorium to produce ^{233}U. Development of a method for detecting the presence of purified thorium or thorium compound in a sealed metal container, including fuel pins (Need 3), would assist in detecting potential undeclared thorium targets that could be clandestinely irradiated in a research reactor or in a commercial nuclear power reactor. Development of a method for detecting the concentration of ^{233}U in a sealed metal container (Need 4) would aid in detecting irradiated thorium targets or concentrations of ^{233}U (greater than 12%) or both with the potential for producing a nuclear explosive.

Needs 1 and 2 address the objective of detecting the diversion of a significant quantity of thorium-containing material from material that has been declared imported/exported for specifically non-nuclear purposes or from a by-product waste stream, in which case it would be exempt from safeguards. Development of advanced information systems with data related to the production of and world trade in monazite, concentrates and products from the thorium minerals listed in Table C-I of Appendix C (Need 1), and waste products containing thorium (Need 2) would facilitate tracking this material to its final destination and verifying its end use in a non-nuclear application.

Needs 5, 7, and 8 address the objective of detecting the production of excess, undeclared, purified thorium at a declared thorium purification facility. A procedure for verifying plant throughput (Need 5) would permit detection of excess ThO_2 or thorium nitrate production. Design verification procedures (Need 7) would help detect production of excess material and diversion of plant product. Moreover, a technique for independently verifying the plant production capacity (Need 8) is required to provide a means of ensuring excess production could be detected.

Needs 6, 9, and 10 address the objective of detecting the clandestine production of purified thorium at undeclared facilities. Environmental monitoring techniques (Need 6) applied both on a wide-scale basis and near suspect sites offer one of the most promising solutions to the problem of detecting undeclared nuclear facilities of any type. Advanced information systems (Need 9) can supply data useful in locating suspect sites through information concerning export of materials related to thorium purification facilities. Development of safeguards approaches (Need 10) for unconventional technologies for extraction, purification, and conversion of nuclear-grade thorium products is essential to detect undeclared facilities using these technologies. The signatures of the processes must be identified before detection techniques for safeguards can be evaluated.

IV. OPTIONS

Options for addressing the aforementioned needs have been listed in Table 3-III. The following identifies the needs fulfilled by these identified options. The needs related to the options are identified by number.

Option 9: Develop instrumentation for detecting and monitoring thorium concentration in plant feed, product, and waste streams

Addresses Needs 2 and 6

The analysis of various environmental samples is a developing technique that may be used to detect undeclared activities in all facets of a proliferation scenario. Laboratory instruments that may be used for analysis include the following types:

- Molecular spectroscopy,
- Chromatography,
- Electrophoresis,
- Gas-chromatograph mass spectroscopy, and
- Laboratory chemical analysis.

Option 10: Develop instrumentation for detecting purified thorium or thorium compounds in sealed metal containers

Addresses Needs 1 and 3

Optimize gamma-ray spectroscopy equipment for detecting and quantifying thorium in containers while minimizing intrusiveness.

Option 11: Develop instrumentation for detecting the concentration of ^{233}U in a sealed metal container

Addresses Need 4

Uranium-233 within sealed containers might be detected and quantified by adapting delayed neutron detection and coincidence counting techniques used for ^{235}U and plutonium.

Option 12: Provide observational skills training to inspectors

Addresses Needs 5, 6, 7, and 8

Increasing the inspector's awareness of techniques related to mining procedures associated with nuclear source material will enhance the probability of early detection.

Option 13: Develop advanced information systems with data related to the characteristics of suspect sites, to the production of and world trade in monazite concentrate, and to concentrates and products produced from the thorium minerals listed in Table C-I of Appendix C

Addresses Needs 1, 2, 5, 7, 8, and 9

Information systems that employ neural network query capability are becoming the leading edge of computer technology. These systems will provide an unsophisticated user with unrivaled capability when conducting data searches and information matching. Development and deployment of these types of systems increases the reliability of the safeguards regime.

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CHAPTER 4

CONVERSION AND FUEL FABRICATION PLANTS

I. INTRODUCTION

A. Process Description

1. Conversion Processes. The first chemical conversion process receives natural uranium ore concentrate and produces uranium hexafluoride (UF_6) as feed for enrichment plants or natural uranium fuel fabrication plants. This type of conversion facility may be separate from the fuel cycle facility that receives its product. According to INFCIRC/153,[1] ore concentrates are not subject to IAEA safeguards until they are converted to UF_6. In enhanced or expanded safeguards concepts, increased consideration is being given to safeguards for source materials, at least to the extent of reporting and tracking source materials.

Further chemical conversion of UF_6 or U_3O_8 (yellow cake) to UO_2, in a metal or chemical form appropriate for reactor fuel, is often an integral process step in fuel fabrication plants. For example, in a typical conversion process, natural or low-enriched uranium (LEU) is received as solid UF_6. Steam is used to sublime the UF_6. The gaseous UF_6 is bubbled through water to produce a UO_2F_2 solution (hydrolyzed). To this solution gaseous ammonia (NH_3) is added to precipitate ammonium diuranate (ADU). The resulting slurry is centrifuged, dried, calcined to UO_2, milled, and blended. The UO_2 is placed in storage or transferred to the fabrication and assembly process.

Other conversion processes are also used. For example, in "dry" conversion processes, UF_6 and steam react in the gas phase to form UO_2F_2. The UO_2F_2 is reduced to UO_2 in a fluidized bed reactor using steam and hydrogen as the fluidizing gases. The UO_2 is then calcined with more steam and hydrogen in a rotary kiln to drive off the last of the fluoride.[2]

Fuel fabrication plants may also receive natural or enriched uranium in the form of solution (uranyl nitrate) or as oxide (UO_2). Fabrication facilities that produce fuel for natural-uranium-fueled reactors may receive uranium as oxide.

2. Fabrication Process. Two types of fuel fabrication facilities are considered in IAEA safeguards planning. One type of fabrication facility handles natural uranium and LEU. Uranium is received in one or more of the chemical forms noted above and is converted into the chemical form used in the fuel (metal, oxide, carbide, or nitride). In plants that fabricate fuel for light-water moderated reactors [e.g., pressurized water reactors (PWR) and boiling water reactors (BWR)], uranium oxide powder is blended, milled, granulated, pressed, and sintered into ceramic UO_2 pellets. The pellets are ground to meet dimensional tolerances and dried.

Scrap is collected in containers, sampled for chemical analysis, and transferred to scrap recovery. Stacks of pellets meeting dimensional tolerances are loaded into cladding tubes, and end plugs are hermetically sealed. In advanced fuel design, pellets of differing enrichments may be used in the same rod, and burnable neutron-absorbing materials (poisons) may be included. The total pellet weight in each individually identified rod or pin is recorded for accountability purposes. The rods are assembled into fuel bundles and are shipped to reactors.

The other type of fuel fabrication facility considered in IAEA planning handles direct use nuclear materials, i.e., HEU and plutonium. HEU is fabricated into fuel for research reactors or other special reactors [e.g., reactors for isotope production, naval propulsion, or space (extraterrestrial applications)]. Plutonium is fabricated into mixed-oxide fuel (MOX) for use in light-water reactors in MOX fabrication facilities where PuO_2, UO_2, and some MOX from the scrap recovery line are blended together, pelletized, sintered, ground to size, and finally loaded into fuel pins. Completed rods are made into fuel assemblies, which are stored and eventually shipped to reactors. Plutonium, ^{233}U, and thorium are used in breeder reactor fuels. Other novel fuel fabrication methods are under discussion such as the Direct Utilization of spent PWR fuel in CANDU reactors (DUPIC), which would remotely refabricate spent fuel from PWRs for further burnup in CANDU reactors without separating uranium from plutonium.

3. Solid-Waste Treatment Process. Fuel fabrication processes may generate large quantities of scrap or waste. In low-enriched uranium fuel fabrication plants, solid wastes are sorted, packaged, and assayed. Burnable materials are incinerated. The ash is nondestructively assayed and either packaged for burial or returned to scrap recovery depending on the assay. Nonburnable materials are assayed nondestructively, compacted, and packaged for burial.

4. Scrap Recycle Processes. Three processes may be used to handle scrap recycling in LEU oxide fuel fabrication plants. The first is for scrap pellets and involves milling, oxidation to U_3O_8, and reduction back to UO_2 powder. The second process is for clean scrap other than pellets. This material is milled, dissolved in nitric acid, and precipitated with ammonia to produce ammonium diuranate (ADU), which is filtered, dried, and calcined to UO_2. The third process handles dirty scrap. This material is oxidized, leached, and dissolved in nitric acid. The solution is purified by solvent extraction and subsequently stripped back into an aqueous phase. ADU is precipitated with ammonia and this material is converted to UO_2, as described above. The UO_2 from these three processes is milled, blended, sampled for chemical assay, and stored or returned to the process.

Most of the nuclear material inventory present is usually contained in items such as UF_6 cylinders and finished fuel assemblies. However, from the point of view of safeguards, fuel fabrication plants are essentially bulk-handling facilities. The inventory of bulk materials in a fuel fabrication facility may be upwards of several hundred tonnes, and it occurs in a variety of forms such as solutions, powder, pellets, rejected material awaiting recycling, and scrap material in heterogeneous forms. The material is distributed over large process areas and there are many interrelated flows. Only limited handling precautions in LEU fabrication facilities are required from the standpoint of toxicity and criticality. Therefore the material is more or less accessible at all stages of the process and at all times. Only the starting point and the final step, the storage of cylinders of feed material and the manufacture of fuel assemblies from fuel rods, have the characteristics typical of an item facility.

In HEU, ^{233}U, and plutonium fuel fabrication facilities, criticality safety is an essential design consideration. Plutonium fuel fabrication must be carried out in contained-atmosphere equipment (e.g., glove boxes) or in cells with remotely controlled process equipment because of considerations including contamination with radioactive and toxic materials, radiation exposure to personnel, and criticality.

B. Proliferation Pathway Analysis

The importance of potential proliferation pathways involving conversion and fuel fabrication facilities, whether declared or clandestine, depends on the fuel cycle context in which they exist. Figure 4-1 illustrates some possible proliferation pathways involving conversion and fuel fabrication facilities and puts them into perspective.

Except for pathways involving diversion of direct use materials, any material diverted from a conversion or fuel fabrication facility must be processed in another facility to produce direct use material, i.e., in a reactor or enrichment facility. Thus, diversion of direct use materials is the paramount concern for facilities that possess them. Pathways not initially involving direct use materials risk detection first when the material is diverted from the conversion or fabrication facility and again when it is introduced or processed at a reactor, reprocessing plant, or enrichment facility, provided the existence of such facilities is known. To enhance the efficiency and effectiveness of safeguards, the IAEA is beginning to evaluate safeguards approaches encompassing more than an individual nuclear facility. Table 4-I lists paths for diversion of nuclear materials from fuel fabrication plants, concealment methods, and anomalies upon which detection of diversion might be based.

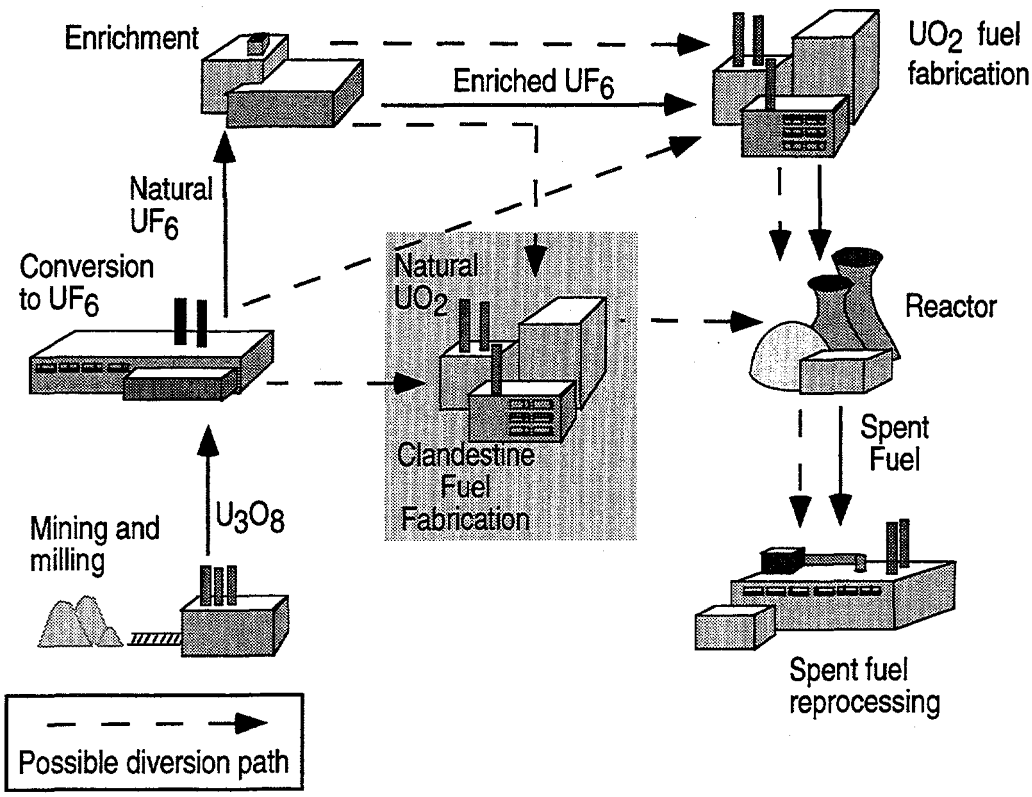

Fig. 4-1. Diagram of nuclear fuel cycle showing possible diversion paths involvingboth declared and undeclared fuel fabrication facilities.

TABLE 4-I. Examples of Diversion Analyses for Fuel Fabrication Plants[a]

Diversion	Concealment Methods	Anomalies	Inspection Activities
This row applies to all the diversions listed below	Falsification of documents	Inconsistencies in documents	Record examination Inventory verification
1. Removal of nuclear material in all kinds of bulk form	Substitution of enriched U with natural or depleted U or inert material	Incorrect composition or enrichment	NDA Inventory verification Use of seals
2. Removal of fuel rods	Substitution with dummies	Incorrect composition or enrichment	Inventory verification
	Substitution with borrowed rods	Rods missing in another MBA	Simultaneous inspection
3. Removal of fuel assemblies	Changing of serial number and offering for double counting	Assemblies missing	NDA Inventory verification
	Substitution with borrowed assemblies	Assemblies missing in another MBA	Simultaneous inspection

[a]Adapted from Table VII in Ref. 3, p. 46.

"For LEU and natural and depleted uranium there is no difference between abrupt and protracted diversion as the detection time is assumed to be one year."[3] At fabrication facilities that possess HEU, ^{233}U, or plutonium, additional safeguards measures and inspection efforts must be concentrated on the direct use materials to achieve the detection-timeliness goal of about one month.

A potentially important proliferation pathway involving diversion of source material (especially natural uranium) is the clandestine or unsafeguarded production of fuel for reactors, particularly any outside of safeguards. Knowledge of the amount of plutonium produced in a reactor usually requires accounting for all the material that has been irradiated in the reactor. For on-load fueled reactors, this requires extra effort although containment and surveillance (C/S) measures and instrumentation have been developed for some types of on-load fueled reactors.

Another pathway that involves activities similar to fuel fabrication is production of material for irradiation in nonstandard ways. For example, fertile material might be fabricated for irradiation in control rods, in blanket or reflector locations, or in otherwise vacant locations within the core or in the fuel assemblies themselves. Another example is the insertion of lithium targets into a reactor for irradiation to produce tritium. Although tritium production may be related to weapons production, tritium is not a nuclear material (as defined by the IAEA). Under current safeguards, the IAEA has no interest in activities that might be related to tritium production, and the facility operator has no obligation to declare such activities. In an enhanced safeguards regime, the IAEA might attempt, at a minimum, to determine whether tritium production was consistent with peaceful activities or was more likely related to weaponization.

A comprehensive understanding by the inspectorate of all activities going on in a fabrication facility might provide detection capability for these types of scenarios. Scenarios involving insertion of fertile materials in nonstandard locations in a reactor might be detected by enhanced safeguards methods applied at the reactor. Insertion of additional fuel rods into fuel assemblies could occur at the fabrication facility, at the reactor, or at an undeclared intermediate location. This scenario can be detected by measurements on fuel assemblies, and continuity-of-knowledge (C-o-K) can be maintained through appropriate sealing systems.

Fuel fabrication facilities can provide opportunities to develop and practice activities related to weaponization. These activities include metal production, uranium or plutonium metallurgy, machining, and welding. In an enhanced safeguards regime, the inspectorate should evaluate the consistency of all processes and activities in the context of the other declared or known fuel cycle activities and objectives in the state.

The rate of plutonium production in a reactor can be increased by increasing the reactor's power. One possibility for increasing reactor power without major redesign of the reactor is to increase the power density by redesigning the fuel to improve its thermal heat transfer characteristics. For example, the fuel surface area might be increased through the addition of fins, and the rate of coolant flow might also be increased by redesign of fuel or by other means (e.g., bigger pumps). Activities at a fuel fabrication facility to develop new or experimental fuel types may indicate the desire or intention to increase reactor power and should be evaluated in the context of the state's other known nuclear activities and objectives.

The current safeguards approach to control the diversion of nuclear materials uses nuclear material accounting and C/S. The objective is to detect an abrupt diversion of a significant quantity within the period of time required to convert it to a usable form and also to detect a protracted diversion rate of one significant quantity per year. Material balance accountability is the main safeguards approach for the protracted diversion scenario, where timeliness is not required. A combination of frequent item accountability and C/S are used to detect abrupt diversion. C/S of materials in containers is achieved via tamper-indicating seals, and C/S of material in process is achieved via inspection by an on-site inspector.

Conversion and fabrication facilities and equipment therein that are subject to safeguards are verified at least once a year by item counting and identification. Safeguards inspections are performed to verify the peaceful use of the facility and equipment listed on the inventory and to provide assurance that all nuclear material produced, processed, or used therein becomes subject to safeguards.

Signatures of conversion and fabrication activities are primarily aqueous and airborne-effluent-containing chemicals associated with the chemical processing steps and wastes generated in conversion and fabrication facilities. These chemicals include HF, NH_3, nitric acid, nitrogen oxides, organic phosphates, hydrocarbons, and fluorides. Other possible signatures associated with UF_6 are the hydrolysis products, UO_2F_2, or the uranyl ion. In acidic or neutral solution (i.e., with excess water), uranyl and fluoride ions are produced rather than solid UO_2F_2. Other signatures may be metals and metal alloys associated with the fuel cladding such as zirconium, nickel, molybdenum, and aluminum. Neutron poisons used in fuel fabrication include gadolinium, hafnium, and boron. Reducing agents that might be associated with production of metal fuels (or with weaponization activities) include calcium and magnesium, either in metallic or oxidized forms. Uranium and thorium could appear in airborne particulates and in liquid wastes in retention ponds. In the case of MOX, these effluents could also contain plutonium.

II. OBJECTIVES

The objectives determined in this study for enhanced safeguards of conversion and fuel fabrication facilities are listed in Table 4-II. The first five objectives are components of the traditional safeguards objective to detect diversion or loss of nuclear material in a timely manner and to detect the nonpeaceful use of facilities or equipment or both (in some INFCIRC/66 agreements). The sixth objective enhances the traditional safeguards objectives by adding the detection of conversion and fabrication activities at undeclared facilities. Timely detection of the diversion of direct use material would have the highest priority. Opportunities to detect diversion of direct-use material beyond the facility are limited to reduction to metal, fabrication, and weaponization activities.

TABLE 4-II. Objectives of Enhanced Safeguards for Fuel Fabrication

Objective 1	Detect diversion of direct use material (HEU, plutonium, or ^{233}U) from fuel fabrication operations at declared facilities
Objective 2	Detect diversion of LEU or natural uranium from fuel fabrication operations at declared facilities (particularly, if on-line fueled reactors are available)
Objective 3	Detect undeclared fuel fabrication activities at declared facilities
Objective 4	Detect suspicious changes to fabrication at declared fuel fabrication facilities, i.e., changes in cladding materials or fuel configuration and the addition of undeclared material to final fuel
Objective 5	Detect suspicious activities at declared fuel fabrication facilities that might be weapons related (nonpeaceful uses), i.e., uranium or plutonium metallurgy and the development of dual-use fabrication techniques such as welding or machining
Objective 6	Detect fuel fabrication activities at undeclared facilities

It is impractical to differentiate the priorities of objectives 2, 3, and 4 except in a situation where on-load fueled reactors are available; then objective 2 would have the highest priority of the three. The proliferation scenarios addressed by these objectives involve several additional proliferation steps with the potential for detection, i.e., reactor operation and reprocessing.

III. NEEDS

Table 4-III lists needs identified by the IAEA in their *Safeguards R&D and Implementation Support Programme 1995-1996*.[4] They address enhancing traditional safeguards approaches to obtain the objective of detecting diversion of materials from these facilities in a timely manner. The following provides a description of each of these needs:

TABLE 4-III. Needs for Enhanced Safeguards of Conversion/Fuel Fabrication Facilities (derived from IAEA's Safeguards Research and Development Program)

Need 1	Procedures and technology for verifying design information, including initial design, and maintaining continuity-of-knowledge of design, especially for MOX fabrication facilities
Need 2	New concepts and approaches for efficient and effective safeguards of conversion and fabrication facilities
Need 3	Verification of transfers to/from fabrication and conversion facilities
Need 4	Verification of the peaceful use of fabrication facilities and equipment
Need 5	Verification of in-process inventory and holdup in MOX fuel fabrication facilities
Need 6	Improved NDA systems; improved reliability, unattended operation, standardization
Need 7	On-site sample measurement and verification systems for samples taken in facilities
Need 8	Upgrade C/S equipment to digital technology
Need 9	Improve safeguards data evaluation
Need 10	Reassess containment devices and seals
Need 11	Remote transmission of safeguards-relevant data
	New Needs for Enhanced Safeguards of Conversion/ Fuel Fabrication Facilities
Need 12	Training to observe suspicious activities related to fuel fabrication
Need 13	Detection of signatures (such as environmental, visual, and thermal) related to fuel fabrication – uranium metal production-reduction processes, uranium oxides, CaF_2, TBP, NH_3, NO/NO_2 – special metals used in fuel cladding – uranium-aluminum systems, special graphite coatings
Need 14	Monitor import/export records for materials and machinery related to fuel fabrication

Need 1: Improved procedures and technology for acquiring and verifying design information

There is a need for a set of procedures for acquiring and verifying design information, including initial design, and a means for maintaining C-o-K of the stated design or changes to the design. This need involves criteria for verifying and maintaining C-o-K. Design information is used to analyze diversion paths and to determine optimum locations for installation of Agency measurements and C/S devices.

Need 2: New concepts and approaches for efficient and effective safeguards of conversion and fabrication facilities

Examine new approaches to make safeguards more cost effective by reducing routine inspections. One approach might be based on an expanded declaration of information by the states together with extended access for verification and greater unpredictability of the Agency's verification activities. Criteria need to be established against which the effectiveness of new approaches can be measured.

Need 3: Verification of transfers to/from fabrication and conversion facilities

A key safeguards activity is verifying material transfers in and out of these facilities. Excessive inspection effort is required for direct verification of transfers. New inspection procedures are needed that would allow effective and efficient use of the Agency's manpower.

Need 4: Verification of the peaceful use of fabrication facilities and equipment

Proposals to strengthen safeguards include a requirement to obtain assurance that facilities are not being used for the development or production of nuclear weapons, i.e., the peaceful use of a facility must be verified. Experience with safeguards agreements under INFCIRC/66 under which "peaceful uses" of facilities are verified might be used to address this problem.

Need 5: Verification of in-process inventory and holdup in MOX fuel fabrication facilities

The verification of the operator's physical inventory by inspectors is a core activity for the standard safeguards approach to MOX fuel fabrication facilities. Techniques for measuring or estimating hold-up in process equipment and transfer lines in these facilities are needed to meet timeliness goals.

Need 6: Improved NDA systems; improved reliability, unattended operation, standardization

Significant enhancements in present equipment/instrumentation are required to meet the safeguards needs in highly automated facilities and facilities with continuous flow processes. Such enhancements include unattended operation, increased reliability, tamper resistance and data authentication, standardization of equipment and software, and optimization and improvement of all components including front-end electronics and radiation detectors.

Need 7: On-site sample measurement and verification systems for samples taken in facilities

The increasing throughput and complexity of new and future facilities requires that the IAEA increase its capability to conduct highly accurate on-site verification measurements to conclude in a timely manner that no diversion has occurred. This requirement includes the need for sample authentication and security (C-o-K). When samples are collected remotely from areas that are difficult to access, it is difficult to verify (authenticate) the source of the sample. When samples require extensive treatment before shipment, the IAEA needs to maintain C-o-K on samples during preparation.

Need 8: Upgrade C/S equipment to digital technology

Surveillance is used to confirm the absence of any interferences with the verified materials. Successful application greatly reduces the remeasurement effort otherwise required. Digital image surveillance (DIS) will ensure more effective and efficient surveillance. DIS offers a much enhanced image filtering system where the emphasis is more on “activity-based imaging” than on “repetitious scene capturing.”

The IAEA has recently completed a field test of a procedure that would permit the inspected party (the facility operator) to remove, replace, and return completed video surveillance tapes to the IAEA without the presence of an inspector. The test suggested that significant inspection effort could be saved, at least with regard to inspections at reactors: the type of facility for which the field test was conducted. To make the procedure viable for real situations, video data would have to be encrypted. This could be accomplished most efficiently and effectively if the data were digital.

Need 9: Improved safeguards data evaluation

The need exists for on-site evaluation of inspection data to reduce the necessity to carry out the data analysis at IAEA Headquarters, which results in delays in inspection activities. This would give the IAEA the capability of near-real-time accountancy (NRTA), a safeguards scheme that could be applied to fabrication facilities.

Need 10: Reassess containment devices and seals

Seals are an important part of safeguards in fabrication facilities to assure the integrity of verified materials. Inspectors receive most of their radiation exposure while applying and checking seals. The use of seals needs to be reassessed in view of a) new technology that may offer more reliable, more flexible, and less costly containment methods; b) increased difficulties in accessibility and environmental conditions; and c) the desire for improvements in cost effectiveness.

Need 11: Remote transmission of safeguards-relevant data

New C/S techniques are needed to improve cost effectiveness by reducing on-site inspection work. Current commercial communications technology allows automatic transmission of information through digital communication channels. This technology could transmit information such as optical surveillance data, electronic seal data, and other monitoring data.

Need 12: Training to observe suspicious activities in fuel fabrication facilities

The need exists to improve observational training of inspectors to include recognition of suspicious activities within fuel fabrication facilities such as modification or alteration to fuel assemblies and weaponization-related activities performed under the cover of conversion and fabrication.

In an enhanced safeguards approach, the inspector should be aware of all the activities being carried out at conversion and fabrication facilities and should evaluate fuel development and other activities for consistency with regard to the state's other nuclear activities and facilities.

Need 13: Detection of environmental signatures related to fuel fabrication

The need exists to enhance the IAEA's ability to detect any undeclared facilities or activities in states with comprehensive safeguards agreements. Environmental monitoring is one approach to this safeguards need. Environmental signatures that may be associated with fuel conversion/fabrication may not be conclusive but would provide additional reasons to look for enrichment and reprocessing activities.

Need 14: Monitor import/export records for materials and machinery related to fuel fabrication

A need exists to strengthen IAEA's capability to make declarations on the presence or absence of undeclared activities by developing methods to collect, categorize, and analyze relevant information from various sources. This includes a need for information management and assessment tools.

IV. OPTIONS

The following options are suggested to meet the needs for enhancing and strengthening safeguards of conversion and fuel fabrication facilities. A listing and categorization of potential options is given in Table 4-IV.

<u>System Studies</u>

Option 1: Develop new safeguards approaches for conversion/fuel fabrication facilities

Addresses Need 2

Investigate new approaches such as NRTA to safeguard new, automated facilities. This is particularly important with regard to detection of diversion of direct-use material from large, automated facilities such as new MOX fuel fabrication plants.

Investigate new national or multiple-facility fuel cycle approaches that would reduce the amount of routine inspection effort. For example, fuel assemblies that do not contain direct-use material must be irradiated in a reactor to produce direct-use material. Fuel assemblies can be verified either at the fuel fabrication plant or at the reactor, and sealing systems can be used to maintain C-o-K. These approaches may require development or improvement of sealing or surveillance systems. Option 4 identified as "Develop new inspection procedures to verify inter-facility transfers" also relates to this option.

TABLE 4-IV. Options for Enhanced Safeguards of Conversion/Fuel Fabrication Facilities

System Studies	
Option 1	Develop new safeguards approaches for conversion/fuel fabrication facilities
Inspection Procedures	
Option 2	Develop procedures for collecting design information
Option 3	Develop procedures and technologies to verify design information for new/modified facilities
Option 4	Develop new inspection procedures to verify inter-facility transfers
Option 5	Develop inspection procedures to verify peaceful use of facilities
Instruments and Methods	
Option 6	Improved gamma-ray data acquisition and analysis
Option 7	Remote, unattended monitoring system integration
Option 8	Instrumentation for in-process verification measurements
Option 9	Detector systems for monitoring SNM
Option 10	Digital image surveillance
Option 11	Electronic seals
Option 12	Ion-beam analysis techniques
Option 13	Trace elemental and isotopic capabilities of inductively coupled plasma mass spectrometry (ICPMS)
Option 14	Portable uranium analysis for enrichment
Option 15	Raman spectroscopy
Training	
Option 16	Observational training
Option 17	Environmental monitoring and sampling training
Information Systems	
Option 18	Develop tools to evaluate the effectiveness of safeguards
Option 19	Atmospheric modeling tools for planning environmental monitoring
Option 20	Management system for information relevant to safeguards
Option 21	Enhance inspector's on-site computing and information analysis capability

Inspection Procedures

Option 2: Develop procedures for collecting design information

Addresses Need 1

Define procedures to reliably collect, evaluate, and assemble design information required to develop an effective and efficient safeguards approach to a facility and to aid in the development of procedures and technologies for design verification.

Option 3: Develop procedures and technologies to verify design information for new/modified facilities

Addresses Need 1

Develop computer-aided methods to evaluate and analyze design information for planned facilities to aid in analyzing diversion paths and optimizing the installation of IAEA nondestructive assay (Need A) measurement and C/S devices. Investigate various technologies for verification of design information, e.g., acoustic resonance, ground-penetrating radar, and gamma-ray imaging techniques.

Option 4: Develop new inspection procedures to verify inter-facility transfers

Addresses Need 3

Investigate new procedures to verify inter-facility transfers that reduce manpower requirements. Consider new inspection strategies such as zone approaches for the entire fuel cycle or random inspections with or without short notice.

Option 5: Develop inspection procedures to verify peaceful use of facilities

Addresses Need 4

Develop procedures to obtain assurance that facilities are not being used to develop or produce nuclear weapons. Experience with INFCIRC/66 agreements, under which "peaceful use" of equipment and facilities is verified, might be used to address this need to strengthen safeguards.

Instruments and Methods

Option 6: Improve gamma-ray data acquisition and analysis

Addresses Needs 5, 6, and 7

Develop computer-controlled gamma-ray data acquisition hardware with software that monitors data acquisition conditions, controls hardware, and advises the operator on measurement conditions to optimize data collection. Improve data-analysis software to adapt analysis to adverse conditions.

Option 7: Remote, unattended monitoring system integration

Addresses Needs 6 and 11

Integrate unattended monitoring, containment (seals), and surveillance systems with commercial communication technology to allow automatic transmission of data. Determine situations for which it is appropriate to transmit safeguards-relevant information. Investigate methods to authenticate and encrypt safeguards data.

Option 8: Instrumentation/techniques for in-process inventory measurements

Addresses Needs 5 and 6

Develop instrumentation and measurement techniques for verifying special nuclear material (SNM) inventory in in-process equipment. Efforts will include the use of the operator's process monitoring equipment through authentication of data from such systems. Verification of in-process inventory and holdup is especially important for large facilities.

Option 9: Detector systems for monitoring SNM

Addresses Needs 5, 6, and 7

Investigate alternatives to liquid-nitrogen-cooled, high-purity germanium detectors for continuous monitoring of SNM in remote, limited-access environments. Assess availability, reliability, and capability of ambient-temperature semiconductor and gas-phase detectors for application to SNM monitoring.

Option 10: Digital Image Surveillance

Addresses Need 8

Utilize digital imaging technology for IAEA's optical surveillance needs. Provide IAEA with capabilities for digital imaging, processing, and storing image data. Provide IAEA with enhanced image filtering systems to improve the effectiveness and efficiency of their optical surveillance applications.

Option 11: Electronic Seals

Investigate more reliable, more flexible, and less costly electronic seals. Electronic seals can be remotely interrogated; thus, they could meet requirements where access is limited.

Option 12: Ion-beam analysis techniques

Addresses Need 13

Investigate ion-beam analysis of particles for detecting signatures of fuel fabrication activities. In particular, look for uranium metal alloys associated with certain types of reactors.

Option 13: Trace elemental and isotopic capabilities of ICPMS

Addresses Needs 7 and 13

Investigate the use of ICPMS for rapid, low-cost analysis of environmental samples to detect conversion/fuel fabrication activities.

Option 14: Portable equipment for analyzing uranium enrichment

Addresses Need 13

Investigate portable measuring equipment to determine uranium enrichment that can be used in the field.

Option 15: Raman spectroscopy

Addresses Need 13

Investigate the use of Raman spectroscopy to identify groups of chemical compounds in the environment, in effluent, and within inspected facilities that may indicate undeclared conversion, fuel-fabrication, and weaponization-related activities being conducted in a fuel fabrication facility.

Training

Option 16: Observational training

Addresses Need 12

Train IAEA personnel to enhance their observational capabilities to recognize diversion, undeclared, or weaponization activities in conversion/fuel fabrication facilities.

Option 17: Environmental monitoring and sampling training

Addresses Need 13

Train IAEA personnel in procedures to collect, segregate, and preserve environmental samples. This training will help ensure that inspectors use appropriate and consistent techniques, thereby increasing the effectiveness and efficiency of environmental inspection activities.

Information Systems

Option 18: Develop tools to evaluate the effectiveness of safeguards

Addresses Needs 2 and 9

Develop data collection and analysis tools to evaluate the effectiveness of the implementation of new enhanced safeguards schemes. These tools will also provide guidance for new safeguards approaches, procedures, instrumentation, and inspection activities.

Option 19: Atmospheric modeling tools to plan environmental monitoring

Addresses Need 13

As part of the IAEA's environmental monitoring, atmospheric modeling tools would assist the IAEA in identifying sources of measured environmental signatures or alternatively assist them in identifying locations where samples might be taken to obtain information on facilities.

Option 20: Management system for safeguards-relevant information

Addresses Needs 2, 9, and 14

Provide the IAEA with information management and analysis tools for a variety of information relevant to the traditional and enhanced safeguards regimes.

Option 21: Enhance inspector's capability to use portable computers to analyze information on-site

Addresses Need 9

Develop software for portable computers that inspectors can use to analyze and assess inspection information at facilities to assist them in conducting inspections.

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CHAPTER 5

REACTORS, ACCELERATORS, AND FUEL IN STORAGE

I. INTRODUCTION

This analysis of pathways for acquiring nuclear materials covers the portions of the fuel cycle between the receipt of fabricated nuclear fuel or target assemblies and delivery of spent fuel or target assemblies for reprocessing or long-term repository storage. The nuclear materials of interest are fissile actinides such as ^{235}U, ^{233}U, and plutonium. One focus of concern is materials produced by conversion of fertile to fissile material in nuclear reactors and particle accelerators. The other concern is the possible theft or diversion of safeguarded fissile material from such facilities. (For this part of the study, theft and diversion are considered equivalent and will be referred to as diversion.) In addition, diversion of nuclear material inventories placed in dedicated storage facilities is considered. Of "lesser" concern is the use of nuclear reactors or accelerators to produce tritium.

A. Reactors

With the exception of HEU, fissile materials that may be used in nuclear weapons (plutonium and ^{233}U) are produced from target materials by nuclear reactions. (Other fissile actinides can also be produced in this manner.) Plutonium (^{239}Pu) is produced by neutron irradiation of ^{238}U. Uranium-233 is produced by neutron irradiation of ^{232}Th. Reactors are the principal devices used for the conversion of fertile material to fissile material. Reactors may be categorized by their fuel, moderator, coolant, and neutron energy. They are also categorized by their design and function. The vulnerability of a reactor to material diversion depends on the reactor design. Although a reactor may contain a significant quantity of nuclear material, the form, location, and radioactivity of the material can affect the difficulty of diversion. Reactor types include research and test reactors, power reactors, breeder reactors, naval propulsion reactors, and production reactors. Naval reactors are of national security interest and are not within the scope of this report. Production reactors are variations of research, power, or breeder reactors designed and operated to produce fissile material.

1. Research and Test Reactors. Research and test reactors have been designed for numerous applications. They span a wide range of design configurations, material types, geometries, and power levels.[1-3] Research reactors are often used as prototypes for larger reactors. Reactor cores may contain plutonium or uranium of various enrichments or both. Safeguards considerations depend on the type and quantity of fissile material used and its accessibility. The IAEA presently has approximately 175 research reactors and critical assemblies under safeguards.[4] Legitimate research reactors are used for isotope production for medical, agricultural, and industrial purposes. These facilities are often designed with mechanical apparatus for exchanging fuel and target material and have extra space for core rearrangement or expansion; thus the possibility for unauthorized use or material diversion is increased.

Power levels in these reactors may range from essentially zero (e.g., critical assemblies) up to several MW (e.g., JRR-3 at 20 MW_t). Depending upon the application, the reactor fuel may not be highly irradiated and thus would be easier to reprocess than highly radioactive power-reactor fuel with high burn-up.

In considering the importance of this proliferation pathway, it is important to remember that, to date, all nuclear weapons states have used research reactors both for materials production and as training sites for nuclear personnel.

A comparison of the differences between research reactors and reactors operated to produce nuclear weapons material is given in Table 5-I.[5]

2. Power Reactors. Power reactors are designed to produce steam for electricity generation. The installed worldwide generating capacity at the end of 1992 was 406 GW_e.[6] Approximately 1 kg of plutonium is produced each year for each 3 MW of electricity generated. Efficient operation of power reactors requires high burn-up of the fissile material in the fuel. As a consequence, the plutonium produced in a power reactor has a high fraction of ^{240}Pu, an isotope that is less desirable as weapons material than ^{239}Pu. However, plutonium obtained from a power reactor can be fabricated into a reduced-yield weapon, so it must still be safeguarded. At the end of 1992, there were 412 nuclear power plants operating worldwide.[6] Reactors are the most numerous type of nuclear facility and require the largest part of the IAEA safeguards resources.[7] Significant effort has been expended to develop safeguards instrumentation and procedures to verify reactor materials inventory. Reactor designs used for power production include[8]

LWR: Light-water reactors are the principal type of reactor used in the US and worldwide. There are two types, PWRs and BWRs. The fuel is LEU (2-5%). The moderator and coolant is H_2O. Fuel cannot be removed from these reactors while they are operating on-line. Consequently, the focus of safeguards has been verification of fuel prior to irradiation and of spent fuel after removal from the reactor.

TABLE 5-I. Differences Between Research Reactors and Production Reactors

Research Reactor	Production Reactor
Fuel Enrichment	
Research reactors acquired from advanced nuclear nations use HEU in a high-power-density configuration (>5-10 kW/L) to produce high in-core neutron fluxes. A country developing an indigenous uranium-mining industry might build natural uranium reactors, such as CANDU (heavy-water-moderated), or graphite-moderated types.	Production reactors typically use natural uranium or LEU in low-power-density (0.01-1.0 kW/L) configurations. Natural uranium, graphite-moderated, air-cooled reactors have been used by most nuclear weapon states for ^{239}Pu production.
Power	
Research reactors are low power (typically <10 MW).	Production reactors are typically 2-50 MW and above. Note: High-power-density reactor cores (>10 kW/L) fueled by HEU could be used only for limited production before the core would need replacement.
Operation Schedule	
Research reactors operate intermittently to accomplish some research program initiatives, e.g., neutron radiography, fuel-element research, and operator or student training.	Production reactors operate on continuous three-shifts-per-day schedules.
Refueling for Plutonium Production	
Research reactors operated intermittently require infrequent refueling (annually or less often). Frequent shutdown of research reactors may indicate weapons-grade plutonium manufacturing.	Production of low-irradiation plutonium requires abnormally high fuel throughput. Typically 25-30% of the fuel would be changed out periodically, with the remaining fuel repositioned toward the outside of the core.
Fuel Elements	
Fuel elements for research reactors are static, specifically designed, custom-fabricated units integrated into the reactor core. Typically, only one spare core and one spent core are stored on-site.	Production-reactor fuel elements are designed for simple placement and removal and must be fabricated and designed for easy dissolution in fuel reprocessing. Abnormally large spent-fuel storage pools or numerous fuel-shipping casks could indicate a capability to store and ship large numbers of fuel/target elements.
Fuel Source	
Research reactor fuel is typically acquired from advanced nuclear countries.	The indigenous capability to manufacture low-tech natural uranium fuel/target elements is required to produce ^{239}Pu in volume.

CANDU: This reactor uses natural uranium fuel and D_2O as moderator and coolant. These reactors are used in Canada, India, and Argentina. Fuel and target material may be inserted and removed from these reactors during power operation. Significant effort has been spent on developing instruments and methods to monitor the transfer of material in these reactors.

Gas-Cooled Reactors: There are numerous variants on this reactor design. Graphite is used as a moderator and the fuel is natural or slightly enriched uranium. In some designs, on-power refueling is achieved. This type of reactor has also been used as a plutonium production reactor in the US, UK, FSU, and China. In the FSU, gas-cooled reactors have had dual use for both power and material production.

An additional source for concern is a nuclear power plant co-located with a seawater desalination plant. Although it is energy intensive, a ready supply of uranium may be obtained as a by-product of the desalination process.[9] Additional information on source material production may be obtained in Chapter 3.

Indicators pertinent to safeguarding power reactors are given in Table 5-II.[5]

3. Breeder Reactors. Breeder reactors are designed to produce more fissionable material than they consume. The principal technology that has been adopted for power generating breeders is the liquid-metal fast breeder reactor (LMFBR). LMFBRs are used to generate electricity in France, Japan, Russia, and the UK. The US has been developing this technology as part of the Integral Fast Reactor (IFR) Program. Other types of breeder reactors that have been designed include the gas-cooled fast breeder reactor, the light-water breeder reactor, and the molten salt breeder reactor. ^{233}U can be produced in light-water breeder reactors by irradiation of ^{232}Th. India, which has abundant thorium resources, is pursuing this fuel cycle. LMFBRs produce plutonium by neutron irradiation of ^{238}U. The plutonium is extracted from the spent fuel at a fuel reprocessing facility. Safeguards requirements for fuel in the reactor and spent fuel should be similar to those at LWRs. Safeguards requirements for fresh fuel will be more stringent if it contains plutonium.

Signatures and indicators for diversion of nuclear material from reactors are given in Tables 5-III through 5-IX, which have been adapted from "Proliferation Detection Technologies."[10]

TABLE 5-II. Indicators Pertinent to Safeguarding Power Reactors

If there are...	it may indicate...
nuclear power plants in operation, under construction, or planned,	a potential source of nuclear material. Note: Material accountability procedures should be established prior to receiving the first fuel shipments.
frequent shutdowns of power reactor,	production of weapons-grade plutonium.
partial replacements of the fuel core,	diversion attempts.
reactors operating with on-line refueling systems (for example, CANDU or RBMK),	a plutonium diversion that is difficult to detect. Note: These remotely operated machines employ sophisticated positioning or alignment systems in conjunction with video monitoring to allow charging and discharging of fuel elements while the reactor is operating.
placements of unnecessary ^{238}U in or around a reactor core (as in-core gamma shields or replacement of reflector materials),	attempts at plutonium production (although the amount might be small if care is not exercised in the location).
increased movements of material in and out of the spent-fuel pool, in conjunction with frequent shutdowns,	attempts to divert material. Note: Spent-fuel elements or production-target elements would be stored, at least temporarily, in spent-fuel pools adjacent to the reactor.

TABLE 5-III. Reactor Operations—Graphite Reactor

Target Signatures	Type of Collection	Collection and Detection Technologies
Graphite	Solid/Waste Impt/Expt Records	Radiation Detection - gamma counting - gamma spectroscopy Mass Spectrometry Neutron Activation Analysis
Fuel Elements	Solid Visual	Radiation Detection - gamma counting - gamma spectroscopy Inspections Video Monitoring
Shipping Casks	Radiation	Radiation Detection - gamma counting - gamma spectroscopy
	Thermal Visual	Infrared Imaging Satellite/Aircraft
Cooling Units, Assoc. Pumps, Exchangers	Thermal Visual	Infrared Imaging Satellite/Aircraft Covert Electronic Video
Hot Water Ponds	Thermal Visual	Infrared Imaging Satellite/Aircraft
Water Purification Facilities	Visual	Satellite/Aircraft
Activation/Fission Products	Airborne Effluent Aqueous Effluent Solid/Waste (burial/storage)	Radiation Detection - gamma counting - gamma spectroscopy Mass Spectrometry Neutron Activation Analysis

TABLE 5-IV. Heavy-Water Reactor

Target Signatures	Type of Collection	Collection and Detection Technologies
D_2O, DTO	Airborne Effluent Impt/Expt Records	SNEC*/Multilateral Cooperation
Fuel Elements	Solid Visual	Radiation Detection - gamma counting - gamma spectroscopy Inspections Video Monitoring
Shipping Casks	Thermal Visual	Infrared Imaging Satellite/Aircraft Covert Electronic Video
Cooling Units, Assoc. Pumps, Exchangers	Thermal Visual	Infrared Imaging Satellite/Aircraft
Activation/Fission Products	Airborne Effluent Aqueous Effluent Solid/Waste (burial/storage)	Radiation Detection - gamma counting - gamma spectroscopy Mass Spectrometry Neutron Activation Analysis

*SNEC = Subgroup on Nuclear Export Coordination.

TABLE 5-V. Light-Water Reactor

Target Signatures	Type of Collection	Collection and Detection Technologies
Shipping Casks	Radiation Thermal Visual	Radiation Detection - gamma counting - gamma spectroscopy Infrared Imaging Satellite/Aircraft
Fuel Elements	Solid Visual	Radiation Detection - gamma counting - gamma spectroscopy Inspections Video Monitoring
Gadolinium	Airborne Effluent	
Cooling Units, Assoc. Pumps, Exchangers	Thermal Visual	Infrared Imaging Satellite/Aircraft
Activation/Fission Products	Airborne Effluent Aqueous Effluent Solid/Waste (burial/storage)	Radiation Detection - gamma counting - gamma spectroscopy Mass Spectrometry Neutron Activation Analysis

TABLE 5-VI. Liquid-Metal Cooled

Target Signatures	Type of Collection	Collection and Detection Technologies
Sodium	Metal/Waste	Chemical
Activation/Fission Products	Airborne Effluent Aqueous Effluent Solid/Waste (burial/storage)	Radiation Detection - gamma counting - gamma spectroscopy Mass Spectrometry Neutron Activation Analysis
Shipping Casks	Radiation Thermal Visual	Radiation Detection - gamma counting Infrared Imaging Satellite/Aircraft
Cooling Units, Assoc. Pumps, Exchangers	Thermal Visual	Infrared Imaging Satellite/Aircraft Covert Electronic Video Monitoring

TABLE 5-VII. Research Reactors

Target Signatures	Type of Collection	Collection and Detection Technologies
Shipping Casks	Radiation Thermal Visual	Radiation Detection - gamma counting Infrared Imaging Satellite/Aircraft
Fuel Elements	Solid Visual	Radiation Detection - gamma counting - gamma spectroscopy Inspections Video Monitoring
Cooling Units, Assoc. Pumps, Exchangers	Thermal Visual	Infrared Imaging Satellite/Aircraft
Activation/Fission Products	Airborne Effluent Aqueous Effluent Solid/Waste (burial/storage)	Radiation Detection - gamma counting - gamma spectroscopy Mass Spectrometry Neutron Activation Analysis

TABLE 5-VIII. High-Temperature Gas-Cooled Reactors

Target Signatures	Type of Collection	Collection and Detection Technologies
Activation/Fission Products	Airborne Effluent	Radiation Detection - gamma counting - gamma spectroscopy Mass Spectrometry Neutron Activation Analysis
Helium	Airborne Effluent	
Fuel Elements	Solid Visual	Radiation Detection - gamma counting - gamma spectroscopy Inspections Video Monitoring

TABLE 5-IX. Underground Reactor Operations

Target Signatures	Type of Collection	Collection and Detection Technologies
Road/Power Lines	Visual Underground Voids	Satellite/Aircraft Penetrating Radar
Personnel	Covert/Overt	HUMINT
Activation/Fission Products	Airborne Effluent Aqueous Effluent Solid/Waste (burial/storage)	Radiation Detection - gamma counting - gamma spectroscopy Mass Spectrometry Neutron Activation Analysis
Waste Heat	Thermal	Infrared Imaging
Spoils/Tails	Visual	Multi-Hyperspectral (satellite)

TABLE 5-X. Accelerator Operations

Target Signatures	Type of Collection	Collection and Detection Technologies
Activation/Fission Products	Airborne Effluent Aqueous Effluent Solid/Waste (burial/storage)	Radiation Detection - gamma counting - gamma spectroscopy Mass Spectrometry Neutron Activation Analysis
Magnets/Magnetrons	Impt/Expt Records	Multilateral Cooperation
Vacuum Equip./Power Supplies	Impt/Expt Records	Multilateral Cooperation
Large Elect. Power Input	Visual	Satellite/Aircraft

B. Accelerators

Intense neutron fluxes can be produced by bombarding heavy metal targets with proton beams.[11-14] A 0.5- to 1.0-GeV proton beam incident on a lead-bismuth target will produce approximately 28 neutrons/proton.[13] The neutrons can be used to breed fissile material in a fertile target. Accelerators can also be used to produce tritium for thermonuclear weapons.

Particle accelerator technology covers a wide range of energies and beam intensities. Production of significant quantities of fissile material will require ion accelerators producing megawatts of beam power. The most intense high-energy beams are produced by linear accelerator (LINAC) technology. LINACs are presently used in pulsed neutron sources in the US and Europe. Examples include IPNS (Argonne), LAMPF (Los Alamos), and ISIS (Rutherford). LAMPF produces an 800-MeV proton beam with a time-averaged current of approximately 1 mA. This type of machine could be used to produce enough plutonium for several fission weapons per year.[14] Accelerators with beam currents over 100 mA are being proposed to breed fissile material for power reactors, for the transmutation of nuclear waste, and for production of tritium for weapons.[12] These machines could produce thermal neutron fluxes greater than 10^{16} n/(cm^2 • s). This is significantly larger than that occurring in any existing reactor.

The operation of a high-current, high-energy accelerator requires more effort and expertise than a research reactor. Consequently, accelerators have not been viewed as composing a significant risk for acquiring nuclear material and have not been subject to safeguards.

Signatures and indicators for possible acquisition of nuclear material from particle accelerators are given in Table 5-X.[10]

C. Fuel in Storage

Storage of nuclear fuel includes storage of fresh fuel and target assemblies as well as irradiated materials and spent fuel. Irradiated assemblies are routinely stored in pools near the reactor until the assembly has cooled sufficiently for processing. Spent fuel may be reprocessed, stored pending future decision on disposition, or disposed of in a geologic or other repository. If the spent fuel is to be reprocessed, it is packaged into shielded casks and transported to a reprocessing facility. Spent fuel that will not be reprocessed[15] must be conditioned for final disposal in a geologic repository. Conditioning places spent fuel and wastes into a form or containment that is acceptable for environmental disposal. If geological repositories are not available to receive spent fuel, interim storage measures may be necessary. Disposal in a geologic repository will involve several phases: excavating the repository, transferring the spent fuel into the repository, emplacing it in drifts, backfilling the drifts, and closing the repository. The first four phases may occur concurrently at different locations within a mature repository.

Spent fuel remains potentially recoverable either before or after placement in a geological formation. Consequently, international safeguards procedures must be applied to the spent fuel from the time of generation at the reactor through geologic emplacement, repository closure, and into the indefinite future. Spent fuel will be considered to be virtually inaccessible for physical verification (a) when the particular area containing it is backfilled or (b) when all repository operations are completed and the repository is closed.

Knowledge of the nuclear material content of spent-fuel items will rely heavily on operator's data and on the continuity of knowledge maintained by the implemented safeguards system. Reactor history and individual assembly identifications will not be important after multiple assemblies are repackaged into a sealed container. The process starting with conditioning of spent fuel and ending with final placement in a permanent repository raises new safeguards problems associated with (a) dismantling and consolidating the assemblies, (b) placing the spent fuel in the disposal container, and (c) C/S, including other monitoring systems, to assure continuity of knowledge of the flow and inventory of the nuclear material. If the integrated safeguards verification fails to provide the assurance required, reestablishing continuity of knowledge by remeasurement may not be possible.

1. Fresh Fuel Storage. Fresh fuel is stored at reactors for refueling. It is composed of natural or depleted uranium, thorium, LEU, HEU, or plutonium in MOX fuel. HEU and plutonium fuels are most attractive for diversion before irradiation in a reactor. LEU fuel is also of concern because it can be converted to feed for an enrichment facility (thus saving a major fraction of the separative work required for production of HEU) or used in a clandestine reactor to produce plutonium. International safeguards for fresh fuel at a reactor is based on item accountability. The quantity of nuclear material is verified at the fuel fabrication facility. At the reactor, the identity and integrity of the spent fuel are verified by inspections during inventory change and during physical inventory. Measurements for gross and partial defects may be performed to verify the nuclear material content of the fresh fuel.*

* A gross defect is a significant quantity or an accountable item that is unaccounted for. A partial defect is when less than a significant quantity or a fraction of an accountable item is not accounted for. Partial defect measurements are typically performed to detect an upper limit (such as not more than 10%) of material missing from a container.

2. Irradiated Fuel Storage. Irradiation of fuel containing natural or depleted uranium, thorium, or LEU produces quantities of ^{233}U or plutonium that can be recovered by reprocessing. The fuel composition, reactor design, and the degree of burn-up determine the quantity of fissile isotopes remaining from the fresh fuel and the quantity of fissile isotopes produced. Spent fuel from most research reactors using HEU is still HEU when removed from the reactor.

3. Reactor Pool Storage. After irradiation, the spent fuel is extremely radioactive and thermally hot due to the decay of the short-half-life fission products. Spent fuel is transferred to a pool and cooled for several years before being placed in a transfer or storage cask. At research reactors the storage pool is an area of the reactor pool. At power reactors the storage pool is connected to the reactor pool by an underwater tunnel, and a cask loading pit is often placed at one end of the pool. Cranes are provided for moving spent fuel assemblies and storage casks. The spent fuel is periodically inspected to verify the presence of specific items. Gross attributes of the spent fuel may be measured through enhanced Cerenkov-glow observation. Partial defects of the fuel can be measured using the gamma-neutron fork detector system.[18] These measurements verify that at least half of the spent fuel is present.

4. Away-From-Reactor Dry Storage. Away-from-reactor dry storage has been implemented in Germany, Canada, and the US, and a dry-storage facility is being constructed in the UK. Current configurations of dry storage include vertical concrete casks (Canada and the US), metal casks for transport or storage on outdoor pads (the US), storage transport casks contained within buildings (Germany), vertical modular storage vaults (Scotland and the US), and horizontal modular storage vaults (the US). The German interim dry storage facility at Ahaus is currently under international safeguards. Safeguards at this facility rely on camera surveillance and radiation detectors in the transfer bay. Casks in the storage bay are not sealed or under camera surveillance. No system exists at the facility to permit unpacking or repackaging of a cask. The Canadian dry storage facility at Point Lepreau is also under safeguards.

5. Spent Fuel Conditioning. Conditioning is defined to be the process of preparing spent fuel (or waste) for environmental disposal. This operation could occur at the reactor, an away-from-reactor storage facility, the repository facility, or a separate facility. In Germany, conditioning will occur at an independent facility. In the US, conditioning will occur at the other three facilities. Conditioning operations result in rebatching of items (casks) into fuel assemblies (or fuel pins if consolidation occurs) and recombining these items into new items for disposal. During conditioning, spent fuel becomes accessible for diversion. Conditioning is scheduled to begin in Germany in 1996 and in the US before the turn of the century.

No conditioning facilities are currently under international safeguards, and an international safeguards approach has not yet been finalized. The favored approach for these facilities is the application of safeguards at the perimeter of the conditioning process cell. This approach is based on item accountability. Undeclared removals of nuclear material from the cell are to be detected by containment, surveillance, and monitoring techniques. Declared removals from the cell are to be verified by a partial-defects measurement.

6. Geologic Repository. A geologic repository is designed to isolate the spent fuel from the environment. However, as the spent fuel cools, the plutonium in the spent fuel will become more attractive for recovery. No spent fuel repositories are currently in operation; however, exploratory excavation of the repositories in the US and Germany has been initiated. These repositories and a small Swedish repository are scheduled to be operated by 2010. Designs for repository operations continue to evolve. Disposal canisters may be contained in shielded casks and set on the floor of the repository, or they may be transferred into vertical or horizontal boreholes in the floor or walls of the repository. Vitrified high-level waste and other highly radioactive wastes will also be disposed of in the repositories.

Safeguards approaches for geologic repositories are currently being developed. The favored safeguards approach for geologic repositories involves frequent, periodic design verification, verification of the spent-fuel items as they are transferred underground, and verification that no spent fuel is removed from the repository. After closure of the repository, safeguards must provide assurance of containment by verifying the geologic formation is not breached. All accesses to the underground facility will be safeguarded to monitor transfers of nuclear material. Information regarding the vault design will be verified and periodically reverified to update IAEA knowledge of the underground facility. The open areas of the underground facility will continually change as new emplacement areas are excavated and filled areas are backfilled. During the postclosure phase of the repository, the following measures have been proposed: site inspections, visual observation of the ground surface, and geophysical techniques to determine the extent of backfill in cavities and to detect other excavations near the repository.

II. OBJECTIVES

The objective of this analysis is to ascertain how nuclear material may be acquired from the facilities containing or capable of producing fissile material. Usable signatures of unauthorized production/diversion should be identified. This includes determining where diversion could occur depending on material type, site type, and the process being performed.

At declared facilities, one objective would be to monitor normal activities to verify proper operation. Another objective would be to recognize abnormal activities, inconsistent with the declared function of the facility, in which unauthorized production or diversion could occur. Inspectors must also be able to detect undeclared facilities and recognize unreported production or storage of fissionable material. Objectives for enhanced safeguards for reactors, accelerators, and fuel in storage are listed in Table 5-XI.

TABLE 5-XI. Objectives for Safeguarding Reactors, Accelerators, and Fuel in Storage

	Objectives at Declared Facilities
Objective 1	Detect theft/diversion of unirradiated HEU, plutonium (direct use material), or other fissile material
Objective 2	Detect theft/diversion of unirradiated LEU (indirect-use material)
Objective 3	Detect theft/diversion of irradiated fuel or target material
Objective 4	Detection of undeclared activity at declared reactor sites
Objective 5	Maintenance of continuity of knowledge of the nuclear material content of fresh fuel and spent fuel items
	Objectives at Undeclared Facilities
Objective 6	Detect undeclared nuclear reactors
Objective 7	Detect undeclared storage facilities
Objective 8	Detect target processing activities
Objective 9	Detect fissile material production or weapons-related activity at an accelerator or other nuclear facility not covered by safeguards
Objective 10	Minimize the impact of effective safeguards on facilities

III. NEEDS

The needs identified by this process establish a set of requirements necessary to accomplish the above-mentioned objectives. The needs include analysis, information, procedures, and measurement technologies that address aspects of the problem. In evaluating needs, it is important to realize that detection of a single "undeclared item or activity" does not necessarily provide proof of unauthorized activity. Needs should be viewed in the context of the entire fuel cycle.

Need 1: Detect and measure unirradiated (direct-use) fissionable material in storage, during transfer, and in vessels.

Need 2: Measure and quantify isotopic composition of unirradiated fissionable material in storage, during transfer, and in vessels.

Need 3: Improve tracking of fissionable material at all points in a facility.

Need 4: Detect, characterize, and quantify releases during reactor, accelerator, or other nuclear facility operation (for example, radiation, radionuclides, thermal, electrical power, electromagnetic emissions, acoustic, and seismic).

Need 5: Detect, characterize, and quantify releases from clandestine production (of fissionable material or tritium) activities (for example, radiation, radionuclides, thermal, and electrical).

Need 6: Detect, characterize, and quantify the composition of irradiated fuel in vessels, during transfer, and in storage (for example, radiation, radionuclides, thermal, and mechanical).

Need 7: Detect, characterize, and quantify the composition of other irradiated fissionable material in vessels, during transfer, and in storage (for example, radiation, radionuclides, thermal, and mechanical).

Need 8: Calculate and analyze isotopic products and potential releases during authorized and unauthorized operations.

Need 9: Measure isotopic composition of irradiated fuel/target material in storage, during transfer, and in vessels.

Need 10: Compare declared operating history with analyses and predict production capability.

Need 11: Monitor and validate declared activity (for example, facility operation, technical expertise, personnel, training, health physics, and safeguards and security).

Need 12: Develop techniques to verify the identity and integrity of spent fuel casks, canisters, and other storage modules.

Need 13: Develop automated, unattended systems to verify the integrity of spent fuel in the various forms in which it may be found in storage. This would include spent fuel in pool storage and during consolidation and conditioning operations and fuel transferred to a repository.

Need 14: Design safeguards approaches and verification procedures for the various storage facilities for spent fuel. These include dry storage facilities and fuel conditioning facilities as well as active and closed repository facilities.

Need 15: Identify facility modifications relative to as-built or previous inspection information. This would include detecting undeclared tunnels and chambers in a repository facility.

Need 16: Develop an integrated verification system for safeguards to monitor the continued emplacement of spent fuel in an active repository, to detect removal of nuclear material, and to monitor the integrity of geologic containment following closure of the repository.

Need 17: Detect the presence of an undeclared reactor facility by the existence of the following items: shielding, cooling system, vessels, fuel and component-handling equipment, environmental release control systems, fuel storage, services (utilities, infrastructure, support), and security.

Need 18: Detect reactor components, e.g., radiation shielding, casks, special moderator (D_2O, graphite), special coolant (D_2O, sodium), cooling system, coolant handling and treatment equipment, vessels, internals, fuel and component-handling equipment, and instrumentation and control system.

Need 19: Detect a storage facility, e.g., shielding, cooling system, fuel and component-handling equipment, environmental release control systems, storage, services (utilities, infrastructure, support), and security.

Need 20: Detect storage facility components, e.g., casks, cooling system, coolant treatment equipment, storage racks, and fuel and component-handling equipment.

Need 21: Detect an accelerator or other nuclear facility, e.g., shielding, power supply, cooling system, component-handling equipment, services (infrastructure, support), and security.

Need 22: Detect components of an accelerator or other unsafeguarded nuclear facility, e.g., vacuum equipment, magnet components, lasers, cooling equipment, high-voltage power supplies, radio-frequency (RF) power supplies, targets, and beam dumps.

IV. OPTIONS

The following are the options (Table 5-XII) for addressing the aforementioned needs. Some options will fulfill more than one need. The needs related to the options are identified by number.

TABLE 5-XII. Advanced Safeguards Options for Reactors, Accelerators, and Fuel in Storage

General Facility Enhancements	
System Studies	
Option 1	Verify design information for new / modified facilities
Option 2	Study areas where bilateral cooperation can improve inspections
Option 3	Identify conditions that should trigger special/enhanced inspections
Option 4	Identify sensitive components for export control
Reactors	
System Studies	
Option 5	Identify safeguards indicators
Option 6	Identify reactor emission signatures
Option 7	Develop fuel cycle isotopics and mass flow information work stations
Option 8	Identify system modifications necessary to convert an integrated research reactor site to a weapons-material-producing site
Option 9	Evaluate options for burning plutonium
Instrumentation, Equipment, and Methods	
Option 10	Develop improved portable uranium enrichment monitors
Option 11	Develop secure authenticated power monitor
Option 12	Develop transportable neutron spectrum and fluence monitors

TABLE 5-XII (cont)

Inspector Training	
Option 13	Demonstrate SNM mass tracking at an integrated fuel cycle facility
Fuel in Storage	
System Studies	
Option 14	Identify safeguards approaches and design requirements
Option 15	Evaluate safeguards timeliness requirements
Option 16	Verify design information for storage facilities
Option 17	Investigate advanced tags/seals
Instrumentation, Equipment, and Methods	
Option 18	Investigate geophysical techniques for monitoring underground storage
Option 19	Develop records management systems
Option 20	Develop techniques for cask integrity verification
Option 21	Measure isotope ratios in irradiated fuels
Option 22	Develop neutron activation tags
Option 23	Improve verification of spent fuel SNM content
Option 24	Develop portable spent fuel NDA system
Option 25	Evaluate optical-materials-based detectors for verification of spent fuel
Option 26	Develop IR imaging for detection of plutonium concentrations
Inspector Training	
Option 27	Provide NDA training courses for inspectors
Option 28	Develop spent fuel verification training program
Accelerators	
System Studies	
Option 29	Identify SNM production capabilities and diversion pathways in accelerators
Option 30	Identify technology to detect or monitor accelerator operation

A. General Facility Enhancements

System Studies

Option 1: Verify design information for new/modified facilities

Develop design-review and acceptance criteria for facilities that handle nuclear materials. The criteria must identify differences between as-designed and as-built facilities that have safeguards implications.

Develop standard format and content guide to be used by facility operators to facilitate the design review process.

Option 2: Bilateral cooperation and support study

Investigate areas in which bilateral cooperation support can provide additional assistance to inspection regimes, in particular, between weapons states where proliferation of weapons design information would be of concern in multilateral inspections.

Option 3: Identify conditions that should trigger special/enhanced inspections

Identify types and sources of information necessary or sufficient or both to trigger non-routine inspections under IAEA or other inspection regimes.

Option 4: Identify sensitive components for export control

Identify components and procedures utilized in constructing nuclear reactors, particle accelerators, and fuel storage facilities. Special attention should be given to the world-wide availability of dual-use components.

Integrate systems used to track components for construction of nuclear facilities with export information systems.

B. Reactors

System Studies

Option 5: Identify safeguards indicators from operating experience

Review typical operating histories of existing reactor designs to identify operational variables and patterns that could be used as safeguards indicators.

Option 6: Identify reactor emission signatures

Compile detailed facility data on the emissions from operating reactors.

Option 7: Develop fuel cycle isotopics and a work station for mass flow information

Develop site-specific algorithms and computer code models to generate fissile material isotopics and mass flow information to assist in assessing the need for an inspection in a facility. Evaluate these algorithms at operating facilities.

Option 8: Identify system modifications necessary to convert an integrated research reactor site to a weapons-material-producing site

Compile in detail the changes in personnel, security procedures, facility emissions, transportation activities, and facility modifications that would occur to transform an existing research site to a weapons material production site. Identify signatures and develop monitoring procedures to flag these signatures.

Option 9: Evaluate options for burning plutonium

Study safeguards options for the elimination of excess plutonium from dismantled weapons. Demonstrate a safeguards approach for a process to burn excess plutonium in a reactor.

Instrumentation, Equipment & Methods

Option 10: Portable uranium enrichment gauge

Develop improved instrumentation to measure the enrichment of ^{235}U in storage. The instrumentation should be portable, automated, and less complex than existing devices. It should be more sensitive to uranium behind shielding or in complicated geometries.

Option 11: Secure authenticated power monitor

Develop a secure electrical power monitor that can be authenticated and is tamper-resistant for detecting, measuring, continually monitoring, and transmitting to remote locations the current and voltage in an electrical transmission line, electrical substation, or power line entering a facility under surveillance.

Option 12: Neutron spectrum and fluence verification

The best indication of reactor performance between inspections is a history of the neutron fluence and spectrum. To monitor these parameters, procedures and transportable instrumentation should be developed to verify neutron spectral indicators and neutron fluence at research reactors.

Inspector Training

Option 13: SNM-mass tracking at an integrated fuel cycle facility

Demonstrate the application of a fissile-mass tracking system in an integrated fast reactor facility. Develop training programs and handbooks specific to safeguards issues at small research reactors, hot cells, and fuel fabrication facilities, for example.

C. Fuel in Storage

System Studies

Option 14: Identify safeguards approaches and design requirements

Identify specific safeguards approaches and system design requirements for geological repositories and conditioning facilities. Design an integrated safeguards verification system for monitoring and verifying spent fuel receipts and shipments.

Option 15: Evaluate safeguards timeliness requirements

Establish safeguards timeliness requirements for the postclosure phase to incorporate consideration of the long time required to access and retrieve nuclear materials from a closed repository.

Option 16: Verify design information for storage facilities

Develop design-information questionnaires and guidance for dry storage, conditioning, and geological repository facilities.

Option 17: Safeguards application of advanced tag/seals

Investigate using prototypes for seals that use intrinsic signatures. These include seals based on ultrasonic and RF technology.

Instrumentation, Equipment, and Methods

Option 18: Underground monitoring

Investigate geophysical techniques to provide information on location and status of spent fuel disposal containers emplaced in a repository.

Option 19: Records management system

Develop records management system to maintain information on the location, depth, and plan area for each repository and the nuclear material inventory for long periods.

Option 20: Cask integrity verification

Develop techniques for identifying and assuring the integrity of casks, canisters, and final-disposal containers.

Option 21: Improve NDA analysis of irradiated fuels

Develop improved NDA techniques to determine isotopic composition of irradiated material. Techniques may combine neutron and gamma-ray detection to measure fission product ratios.

Option 22: Activation tags

Develop multiple isotope tags that will be activated by the neutron flux from plutonium in a container under safeguards. The ratios of several radionuclides will allow one to determine if there has been any discontinuity in exposure.

Option 23: Verify SNM content of spent fuel

Improve radiation-based methods to verify the fissile material content and isotopic composition of spent nuclear fuel in storage. Utilize real-world experience at existing reactor research facilities to identify optimal indicators.

Option 24: Portable spent-fuel NDA verification system

Develop NDA measurement techniques for spent-fuel rods, assemblies, canisters, casks, and disposal containers. Improve high-resolution gamma-ray and neutron instruments used to assay spent fuel in a storage pool.

Option 25: Optical-materials-based detectors to verify spent fuel

Evaluate the potential of scintillating optical fiber technology to measure attributes of spent fuel in storage.

Option 26: Detection of plutonium concentrations

Utilize IR-imaging technology to locate concentrations of plutonium by heat evolving from it.

<u>Inspector Training</u>

Option 27: NDA training courses at Category 1 storage facilities

Develop courses and training facilities to accommodate the increased demands for training IAEA inspectors. The facility should have Category-1 physical security measures to accommodate SNM and the presence of foreign nationals.

Option 28: Training program for spent-fuel verification

Develop programs to train inspectors in the verification of the fissile mass of spent fuel and isotopics at an integrated reactor/fuel reprocessing facility.

D. Accelerators

<u>System Studies</u>

Option 29: Identify weapons material production capabilities and diversion pathways for weapons material in accelerators

Conduct a study characterizing the production of weapons materials using high-current particle accelerators.

Option 30: Identify technology to detect accelerator operation

Survey existing instrumentation and procedures to monitor emissions from particle accelerators (e.g., RF fields).

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CHAPTER 6

SPENT FUEL REPROCESSING

I. INTRODUCTION

Spent fuel reprocessing is a key part of the nuclear fuel cycle, whether for recycling usable fuel for electrical power production or for recovery of plutonium to be used in weapons. For efficient operation, no nuclear reactor burns all of the fissile ^{235}U in the fuel charge. Plutonium is always produced by the operating reactor, with amounts and isotopic mixes dependent on the reactor, fuel types, and the burnup. An LWR will produce approximately 25 kg of plutonium annually per 100 MW of power when the fuel is burned for a normal life of 30 to 40 MWd/kg.[1,2] The isotopes ^{239}Pu and ^{241}Pu, which have a large thermal neutron fission cross section, constitute approximately 60 to 70% of the plutonium discharged from a power reactor under normal operating conditions. A heavy-water reactor is operated to lower burnup and produces less plutonium, but the plutonium isotopics are approximately the same as in plutonium from an LWR. A breeder reactor will produce more plutonium than an LWR because it is operated to higher burnups of 100 MWd/kg or greater. The fissile fraction depends on the location in the core, with a $^{239}Pu/Pu$ ratio exceeding 0.95 in the outer blanket.

There are many reasons to process spent nuclear fuel: to make more complete use of the fissile content of the nuclear material, to reduce the hazards and costs associated with handling the high-level nuclear waste, and to extract useful byproducts from the stream.

Spent LWR fuel generally contains around 0.9% fissile ^{235}U in addition to the plutonium bred from the ^{238}U during reactor operation. These quantities make it hard to ignore this potential resource; recovery and use of this fissile material reduces the need for new uranium acquisition and enrichment by as much as 30%. The most common proposal for use of the plutonium is to include it in a MOX fuel element, which will generally contain about 3% $^{239+241}Pu$. As MOX fuel continues to be recycled through the reactor and reprocessing sequence, the relative amount of fissile plutonium isotopes decreases. Thus, the total plutonium content must increase enough to maintain the plutonium fissile capacity of the final fuel elements. This kind of recycling has the nonproliferation advantage of reducing the effectiveness of the plutonium in nuclear weapons and substantially increasing the handling risks because of the relatively high specific activity of the ^{238}Pu.

Reprocessing may even be attractive in a "once-through" sequence in which plutonium is not recovered for re-use but is separated to reduce long-term storage costs. This has the nonproliferation disadvantage, over storage as spent fuel, that diversion of material into a clandestine nuclear weapons program becomes more difficult to detect.

Diverting material from a commercial nuclear power cycle is not the only way for proliferators to obtain a supply of plutonium for a weapons program. They may choose to operate some sort of non-power reactor to obtain the material. This might include the use of a dedicated (probably clandestine) production reactor or research reactors. The obvious advantages to using a production reactor include a greater material output and the ability to optimize the reactor operating parameters to generate high-quality weapons-grade material. Disadvantages include the specific resource commitment required and probably an increased risk of detection. Using output from a research reactor basically reverses these advantages and disadvantages.

A. Pathway Description

All of these production methods need some kind of spent fuel reprocessing capability, which has four basic components: staging areas for the spent fuel, a fuel element disassembly and dissolution area, a chemical separations process, and a waste handling capability.

Normally, spent fuel is held for a period of 1-1/2 to 2 years after it is removed from the reactor, usually in some kind of water-filled storage pond. During this time, the short-lived fission and activation products generate a tremendous amount of intense radiation. This means the spent fuel storage facility must be heavily shielded—to protect operating personnel and to avoid detection in a clandestine program. This intense radiation also generates considerable "decay heat," so the facility must be equipped to cool the storage area and vent this heat somewhere.

After the heaviest radiation and heat-generating capacity have decayed away, the fuel can be transported to the reprocessing facility. Because the material is still quite radioactive, heavily shielded shipping casks must be employed for this transfer. This, in turn, means that the shipments will need to move by rail or by very heavy-duty truck transport. After they arrive at the reprocessing facility, the fuel elements typically spend more time in storage before they are processed. These materials continue to give off gaseous radiation products and considerable heat, so the spent fuel storage area needs to be equipped with adequate shielding, equipment to handle the radioactive effluents, and enough cooling to avoid excessive heat buildup.

The dissolution head-end generally consists of two parts. The first is an area where the actual fuel and fission products are physically separated (as much as possible) from the cladding and other structural elements of the core material. The second is the actual fuel dissolver itself.

Most fuels that might be reprocessed consist of UO_2, and possibly PuO_2, encased in a ceramic matrix. Further containment is provided by an outside cladding component—generally made of zirconium alloy, aluminum, or stainless steel. The structural and cladding parts of some forms of BWR fuel can be extensively disassembled, whereas the end portions of common PWR fuel assemblies must be forcibly cut off. After disassembly and decladding, the fuel pins themselves are cut into small (3 to 5 cm) chunks before going to the dissolution area. In most cases, this step is accomplished using a shearing knife, but laser-based methods have also been examined. The chunks of fuel may also be run through a crusher to further fracture the structure before the leaching step. The fuel releases volatile fission products trapped within the fuel, so this part of the plant must have off-gas treatment facilities.[3]

In the dissolver unit, which is usually made from heavy stainless steel or titanium, the oxide fuel material is leached away from the non-fuel materials in boiling nitric acid. Very strong acid (6 to 10 M or higher) is most often used; this will generally dissolve all the fuel material. For some kinds of fuel, a nitric acid reflux assembly could be used to dissolve everything—aluminum, uranium, and fission and activation products. This avoids the chop-leach sequence and assures that all the fissionable material goes into the plant input but generates considerably more waste. The residual undissolved hulls are tested to ensure that all the fissile material has been leached away. These materials then become part of the plant solid waste stream, along with the pieces left from the disassembly and decladding operation. Volatile fission products are also released during the dissolution sequence, and various less volatile fission products can be entrained as light aerosol materials in the off-gas stream.

Sometimes small amounts of fluoride may be added to the nitric acid dissolution media to improve the rate. Fluoride ions form strong complexes with some of the metal ions involved (aluminum and especially zirconium), thereby improving their solubility. In some systems, mercuric nitrate is used as a kind of catalyst to "de-passivate" the aluminum surface; otherwise a thin oxide coating may inhibit the dissolution. This aluminum dissolver solution is a good feed material for the solvent extraction process because the high aluminum and nitrate ion content provides an effective "salting" capacity.

Fuel materials embedded in a zirconium metal matrix are more difficult to handle, mainly because hydrofluoric acid must be used for the dissolution. Hydrofluoric acid is a very hazardous material and causes rather severe corrosion. To minimize such problems, zirconium head-end equipment may be fabricated from Monel alloy or Zircalloy C-4. These corrosion problems are aggravated by the fact that the reaction between zirconium metal and hydrofluoric acid generates considerable heat.

Neutron poisons such as boron (usually as boric acid), cadmium, or gadolinium are sometimes added to the dissolution media to provide added assurance of nuclear criticality control.

The most common method used to separate uranium and plutonium from the other materials in the spent fuel is solvent extraction. The first solvent used for large-scale actinide extraction was methyl isobutyl ketone ("hexone"). Although hexone is an effective extractant, it tends to decompose slowly in the presence of strong nitric acid. Some reprocessing variants replace hexone with β,β'-dibutoxy diethyl ether ("Butex")—this extractant gives good separations, is safer to use than hexone, but is more expensive. However, the preferred extractant is generally TBP mixed with a form of kerosene. This material provides good separations (better than Butex), is fairly stable, and is itself less flammable than hexone. The use of TBP for this separation is the basis for the "Purex" process.

In a "generic" extraction process, the dissolver solution is first treated with an oxidant to ensure that the actinides are in their higher oxidation states—primarily UO_2^{2+} and Pu^{4+}, and possibly some PuO_2^{2+}. Probably the most common oxidant used for this step has been potassium dichromate. The treated solution is then processed through a column where it is contacted with the organic extractant. A high-nitrate level is maintained in the input solution so the uranium and plutonium ions will form mixed complexes with the extractant and pass into the organic phase. A general reaction is

$$Pu^{4+}(aq) + 4\,NO_3(aq) + 2\,E(org) \rightarrow Pu(NO_3)_4E_2(org) \quad ,$$

where E denotes the extractant species (TBP for the Purex process) carried by the organic stream. Typically, over 99.5% of the uranium and plutonium is extracted into the organic phase during this step. This process leaves most (around 99%) of the fission products in the aqueous (waste) phase. This high-level radioactive waste solution is sent to some kind of shielded storage facility.

The organic extractant is next contacted with another reagent for further partitioning of the actinides—this solution contains a reducing agent and possibly aluminum nitrate and ammonium nitrate to maintain a high-nitrate level. The reducing agent converts the transuranic actinides to non-extractable oxidation states (+3 for plutonium). Commonly used reducing agents include ferrous sulfamate, sodium nitrite, or hydrazine. Plutonium, and other transuranic actinides, back-extract into the aqueous phase, where the plutonium can be treated by further oxidation-reduction cycles to isolate and purify it. The organic stream with the purified uranyl nitrate is sent to another column where the uranium is stripped into dilute nitric acid.

One disadvantage of the Purex process is that high radiation fields decompose TBP into lower phosphates and butyl alcohol. These materials tend to form strong complexes with many fission products, which may then contaminate the plant actinide stream. To avoid this problem, the recycle TBP stream is treated by successive rinses with sodium carbonate, sodium hydroxide, and dilute acid to remove the degradation products.

The final solvent extraction products are purified solutions of uranium and plutonium nitrates. These may then be converted to various oxides and probably into their respective fluorides.

Other reprocessing options also exist such as selective precipitation and ion exchange. These are not attractive for large-scale operations but remain a proliferation concern with countries wanting a small number of nuclear devices.

The final area of the reprocessing facility is the waste-handling portion. These byproduct solutions are intensely radioactive (the decay heat will literally boil off the water) and usually highly corrosive. Shielded storage tanks, equipped with off-gas treatment and cooling modules, are needed to handle the large quantities of material generated by any significant reprocessing effort. Because of the safety problems associated with handling large quantities of such extremely hazardous materials, some form of immobilization process is worth considering. Immobilization techniques currently in use include converting the material to a stable dry oxide powder or to an oxide glass form.

Safeguarding the nuclear materials associated with a reprocessing plant is complicated by the many different physical and chemical forms involved, including fuel core structures, cut up fuel pins, dissolver solution, actinide complexes held in non-aqueous media, highly radioactive waste solution, very concentrated and pure actinide solutions, dry uranium and plutonium oxide, and possibly volatile actinide hexafluorides. Most of these forms require careful consideration of radiation safety and criticality control factors. Keeping track of where these materials are and how much there is requires the use of many unique and different measurement techniques. These problems are compounded by the wide variety of equipment needed to handle the materials, for example, fuel casks, storage canisters, dissolver vessels, mixers, and separation columns—plus an incredible array of interconnected tanks, pipes, pumps, and valves.

Current international safeguards for reprocessing plants rely on materials accounting as a fundamental measure with containment/surveillance as a complementary measure. The IAEA independently verifies operator's declared measurements of all transfers into and out of the facility and material contained in the facility on a monthly basis. Approaches are being developed for near-real-time accounting (NRTA) that are based on measuring material as it moves through a reprocessing plant. These should improve its ability to detect loss of a significant quantity over a one-month period. The operator is required to perform an annual physical inventory, which is independently verified by the IAEA. The inspector may draw samples for independent analysis or may use the operator's data if the measurements can be verified, for example, by using inspector standards or authentication of operator's equipment.

B. Signatures

Many signatures are associated with the equipment and activities required for nuclear fuel reprocessing. Traces of the actinide and fission products may appear in any aqueous waste generated by rinsing the fuel assembly structural and cladding material, and those undissolved materials will appear in the solid waste from the plant.

Gaseous signatures from a conventional leaching method may also appear in the off-gas. Certain low-volatility species may also be aspirated into the off-gas stream, including traces of uranium and plutonium as well as boron, cadmium, or gadolinium species if these are used as neutron poisons. If an aluminum decladding step is included in the process, sodium hydroxide may also appear. All of these signatures would also appear in the aqueous effluent from the head-end area. Accumulations of the less volatile materials could also appear as signatures in the solid waste from the plant (on off-gas filters and decontamination paraphernalia).

Chemical signatures for Purex solvent extraction include TBP and its degradation products, kerosene and other hydrocarbon solvents, ferrous sulfamate, activation and fission products, NO_x and ammonia, uranium, plutonium, and mercury catalyst. Most of these are expected to appear in both the gaseous and aqueous effluent streams; the radioactive materials are also expected to appear in any solid waste disposal routes. Other chemical signatures might include the boric acid, cadmium, and gadolinium used as neutron poisons. If an alternative separation method is used, hexone or Butex might appear as a signature.

Radioactive signatures for the two smaller-scale separation methods—selective precipitation and ion exchange—are essentially the same as those noted above. Fission and activation products may be aspirated into the airborne effluent from selective precipitation and are likely to appear in the aqueous and solid waste streams for an ion exchange sequence. Acetate or phosphate residues could appear in the aqueous waste stream from a precipitation process. Finally, even a small-scale ion exchange process requires rather specialized resin materials—this could provide an "up-front" acquisition signature and might have a solid waste disposal signature.

Non-chemical signatures associated with the dissolution and separation activities include waste heat, mixed spoils or tails, and silver-containing filters. Signatures associated with waste handling include buried tanks, waste storage ponds, seep basins, and solid waste disposal areas. Other, more general, signatures include corrosion resistant tankage (and, by inference, piping and valves), special railway systems, shielded casks, general radiation shielding, radiation monitoring equipment (plus criticality alarms), HEPA filters, and plant security systems.

II. OBJECTIVES

The objectives identified in this study are listed in Table 6-I. These objectives emphasize enhanced safeguards. The safeguards environment may dictate which objectives are most important, so numbers given do not reflect priority.

TABLE 6-I. Objectives for Reprocessing Facilities

Objective 1	Detect and monitor mining, concentration, milling, and refining of uranium source material at a declared site.
Objective 2	Strengthen traditional safeguards to improve effectiveness and efficiency. This issue was at least partially addressed in the international forum LASCAR (safeguards for LArge SCAle Reprocessing plants), which recommended the use of advanced accountancy techniques such as NRTA or adjusted running book inventory in coordination with improved C/S measures.
Objective 3	Provide increased transparency in safeguards measures that are applied to increase confidence within the international safeguards community. Increased transparency could also improve the efficiency of traditional safeguards by reducing inspector functions.
Objective 4	Provide the capability to detect undeclared reprocessing activities in declared facilities. These facilities could include reactor reprocessing plants or facilities declared to recover selected fission products for resource extension or actinides for waste management.
Objective 5	Detect undeclared facilities at declared or undeclared locations. This activity would require a broad new set of IAEA safeguards activities, including use of information supplied by member states obtained through national technical means and environmental monitoring.

Reprocessing facilities are generally difficult to safeguard due to the large material throughput and difficulty in reducing uncertainties associated with quantitative measurements of material at various processing steps. Objectives 1 through 4 are generally to reduce those uncertainties and improve confidence in safeguards at declared facilities. Objective 5 can be useful in reducing the international safeguards burden in some states because high confidence in the absence of any reprocessing capability might permit the relaxation of timeliness criteria at other stages in the fuel cycle.[5]

III. NEEDS

Table 6-II lists identified needs for enhancing safeguards at reprocessing facilities. The following provides a description of each of these needs.

TABLE 6-II. Needs for Advanced Safeguarding of Reprocessing Facilities

Need 1	Improved tamper indicating devices
Need 2	Better design verification and reverification methods
Need 3	Better means to authenticate branched and logged operator data
Need 4	Improved capabilities to quantitatively measure plutonium in various waste forms
Need 5	Improved capabilities to measure uranium and plutonium content of spent fuel in storage
Need 6	Easier or faster methods to verify tank volumes
Need 7	Improved in-process uranium and plutonium measurement methods to support NRTA
Need 8	Better application of automated measurement methods to support NRTA and inspections
Need 9	Improved information handling tools for inspectors in the field
Need 10	Improved information handling tools for inspectorate
Need 11	Improved definition and evaluation of probable diversion signatures
Need 12	Better procedures for special inspections
Need 13	Better training to help inspectors recognize undeclared reprocessing activities at any kind of nuclear site
Need 14	Improved rapid response capabilities for special inspections
Need 15	Environmental monitoring methods to detect radioactive reprocessing signatures
Need 16	Environmental monitoring to detect non-radioactive reprocessing signatures
Need 17	Improved unattended surveillance equipment
Need 18	Wide-area monitoring surveillance equipment

Need 1: Improve tamper indicating devices (TID, primarily seals) to make it impossible, or at least more difficult, to secretly remove SNM from a storage area or shipping container

Tags supplement such seals by providing unalterable identification of the material, thereby preventing substitutions. Basically, the goal is to provide continuity of knowledge for stored or shipped materials, including safeguards samples as well as the original material. Some of the problems that have been identified for some TIDs include some that are difficult to apply in contained working areas (like inside a glove box), poor performance, and degradation in harsh environments. There are also needs to reduce cost, make TIDs easier to verify during an inspection, and improve manufacturing processes.

Need 2: Better methods to verify, and later re-verify, the design information for a reprocessing facility.

This must involve ways to collect valid information on the plant design and to analyze the design to determine its potential for diversion. For example, how readily might the design be modified to support a hidden proliferation activity? Later re-verification that such a change has not taken place is also critical. Again, the phrase "continuity of knowledge" applies because obviously intermittent verification cannot assure that a system has not been changed to perform some clandestine proliferation work and then changed back before the inspection.

Need 3: Better means to authenticate branched and logged operator data

This requires some form of signal authentication to show a clear connection between the signal origination point and where it enters the safeguards system. Because many different signals are likely to be of interest, a suite of applicable tools will probably be required. In addition, a system that the inspector could bring to the facility, interconnect to the plant data system, and use to independently interrogate and verify every key link in the safeguards information flow would enhance confidence in operator data.

Need 4: Improved capabilities to quantitatively measure plutonium in waste forms to verify that it has not been recovered for clandestine use in weapons production

For example, scrap structural materials or leached hulls can produce a quite inhomogeneous matrix, thereby negating the measurement capabilities of many methods. In principle, a proliferator might use this fact to hide a deliberately incomplete dissolution with subsequent diversion of the nuclear material. Similarly, immobilization solids generated from liquid waste are difficult to verify. For example, it is known that inadequate compensation for so-called "edge effects" and other inhomogeneities make gamma scanning unreliable for verifying the content of waste containers (or fuel storage modules).

Need 5: Improved capabilities for inspectors to verify the uranium and plutonium content of spent nuclear fuel held in storage

The European Safeguards Research and Development Agency working group has stated that standard passive neutron counting methods based on the shift register approach provide "acceptable" results for plutonium but require a close knowledge of the isotopic content. They state that multiplicity methods are currently improving but do not appear to be ready for general field deployment.

Need 6: Easier or faster methods for use by inspectors to verify the tank volume

A key part should probably involve the verification of the software used to generate and apply complex tank calibration curves. It has been stated that much still needs to be learned about the specific equipment and methods to be used, appropriate methods of calibration and recalibration, appropriate and defensible data handling, and phenomena that make it difficult to obtain accurate and reliable verifications. This need is closely connected to a need to develop and deploy better techniques for verifying the mass of a process solution. Use of weight tanks such as the UK has installed at THORP may solve the problem.

Need 7: Improved in-process uranium and plutonium methods to provide better NRTA

Advanced NRTA techniques may help reduce the burden on inspectors because apparent discrepancies can be isolated to a specific time and location. Effort can then be focused quickly in the appropriate area.

Need 8: Better application of automated measurement methods both for NRTA and during inspections

This need has two key features. First, rapid automated methods should allow the operator to more closely approach a true near-real-time material balance. Second, the use of automated techniques should help stretch the resources of the international inspector. Areas of potential automation occur throughout the reprocessing sequence—measurement of stored spent fuel, many kinds of process solution analyses, and verification of the reprocessing plant output.

Need 9: Improved information-handling tools for inspectors in the field

This is a very broad need. First, data collection equipment and methods need to be streamlined for the entire process—for example, rapid identification of key data collection points and elimination of manual transcription. Once the inspector has the data in hand, it would be useful to provide a quick analysis to highlight significant features and perhaps guide further inspection activities or follow-up queries. Finally, information might be transmitted to a central location for more extensive evaluation. If the response could be made quickly enough, the off-site evaluator might be able to interact with the inspector to suggest further specific activities or follow up.

Need 10: Improved information handling tools for the inspectorate

The quick turn-around capability noted above would be desirable—but better data review and analysis capability, in general, are a necessity. There is currently a strong interest in the possible applicability of such tools as neural nets, expert systems, and intelligent front ends for databases.

Need 11: Improved definition and evaluation of probable diversion signatures

The key here is to be able to distinguish between normal, allowed activities and those that might signal additional clandestine activities. Of course, this is no easy task because any signatures from a clandestine activity would be masked by the (presumably) legitimate reprocessing activities. Unfortunately, the only way to detect this kind of situation may be to look for discrepancies in resource expenditures and the level of effort involved. For example, possible indicators might include the quantities of reagents consumed, the amount of radioactive waste being generated, and the number of specific kinds of people working at the facility. If these resources are greatly in excess of the normal levels expected for the declared activities, this might indicate that an additional clandestine effort was in progress.

Need 12: Better procedures to handle special inspections and other non-routine inspector activities

Preparation of these procedures would be largely dependent upon the task above—one cannot teach the inspectors what to look for until one knows what to look for.

Need 13: Better training for inspectors to help them detect undeclared reprocessing activities at any kind of nuclear facility

Preferably, the focus should be on signatures and indicators that an inspector can detect using a minimum of equipment and without needing to collect a huge mass of data. This will simplify the procedures, reduce the total amount of training required, and ultimately make it more likely for inspectors to succeed when they actually go out into the field to perform an inspection.

Need 14: Improved rapid response capabilities when a special, or other non-routine, inspection is triggered at a reprocessing facility

This topic has four basic features. First, it must take into account the triggering method—the certainty afforded by the trigger and the urgency of the response triggers. Second, the state of the possible clandestine activity will affect the level of response—a hidden reprocessing system that is actually operating is clearly more critical than one that is only under construction. Third, the level of cooperation expected must be considered—a totally hostile environment certainly limits the response options available. Finally, logistical factors must be examined, largely depending upon the specific location of the suspect activity. The response definition should evaluate all these factors to define the necessary combinations of procedures, manpower levels and skills, equipment, support structure needed, and post-inspection assessment methods.

Need 15: Environmental monitoring methods to detect radioactive reprocessing signatures

Major improvements in this area are most likely to arise from advances in methods for environmental monitoring. Major efforts should focus on improving the sensitivity of the methods used to measure distinctive reprocessing signatures in dispersed air samples and downstream surface waters. Of course, improvements in the measurement instrumentation will need to be combined with improvements in sampling methods used. Unless the measurements are made in the field, means for ensuring sample integrity during transport and maintaining a verifiable chain of custody will also be necessary.

Need 16: Environmental monitoring methods to detect nonradioactive reprocessing signatures

This simply repeats the needs and caveats noted above for the work on improving the detection of radioactive signatures.

Need 17: Improved unattended surveillance equipment

The main purpose of this capability would be to reduce the frequency of routine inspections. For example, it is recognized that TIDs are useful in providing assurance of container integrity and identity, but current systems do not provide a continuous monitoring capability and therefore cannot qualify as an "alternative measure." Basically, this is a wide open area in which many possible techniques could be studied for their applicability to monitoring such things as fuel storage areas, key process equipment, and product containers.

Subsets of this "remote unattended surveillance" need would involve specific sensors and methods—for example, means for visual confirmation of activities, monitoring thermal and radioactive effluents, and verifying the continuity of an electronic seal or valve monitor. Some of the possible areas would include digital imaging systems, video surveillance, RF motion detectors, radiation signature detectors, light beam (conventional or laser) item monitors, and ultrasonic methods. Front-end triggering of cameras using these sensors will provide rapid response.

Need 18: Better methods for providing remote unattended operation of wide-area-monitoring surveillance equipment

The main purpose of this capability would be to reduce the cost of monitoring for clandestine reprocessing activities across a broad area. Although specific measurement capabilities would be desirable, remote unattended sampling—coupled with methods for ensuring longer-term sample integrity between collection visits—might provide an acceptable alternative.

IV. OPTIONS

The following options are suggested to meet the needs for enhancing and strengthening safeguards of conversion and fuel fabrication facilities. A listing and categorization of potential options are given in Table 6-III.

Option 1: Verify design information for new or modified facilities

Addresses Needs 2 and 11

System studies of design verification/reverification of reprocessing plants can help to optimize technical R&D proposals by identifying key proliferation concerns within these facilities. Once safeguards "holes" are properly identified, technology can be developed to patch the holes.

Option 2: Study areas where bilateral or improved cooperation between the IAEA and specific countries can improve inspections

Addresses Needs 2, 3, and 11

Bilateral cooperation may be the key to solving many reprocessing concerns. This is particularly the case in former Soviet republics and the US, where reprocessing activities will be necessary for environmental and safety reasons, but no international safeguards are in place. New cooperative regimes with the IAEA may make it possible for other countries to permit installation of authentication equipment or new measurement methods. Details of new cooperative agreements will depend on the country being considered.

TABLE 6-III. Options for Reprocessing Facilities

System Studies	
Option 1	Verify design information for new or modified facilities
Option 2	Study areas where bilateral cooperation can improve inspections
Option 3	Identify conditions that should trigger special or enhanced inspections
Instrumentation, Equipment, and Methods	
Option 4	Develop improved TIDs
Option 5	Develop technologies that can detect changes in facilities
Option 6	Develop better means to authenticate branched and logged operator data
Option 7	Use neutron activation to quantitatively measure waste streams
Option 8	Improve algorithms for acquiring and correcting gamma-ray data for fission product backgrounds
Option 9	Develop image processing algorithms to detect design changes and material transfers
Option 10	Establish a rapid response team of reprocessing and materials control and accounting experts for special inspections
Option 11	Use environmental monitoring to detect reprocessing signatures
Inspector Training	
Option 12	Provide inspectors with observational training to detect inconsistent equipment
Option 13	Develop easily accessible data base to improve information handling

Option 3: Identify conditions that should trigger special or enhanced inspections

Addresses Needs 12 and 14

Establishing procedures for calling special inspections may make such inspections more acceptable for the international community. These procedures are not likely to include all possible contingencies, so they should not limit the right for special inspections, but should identify conditions under which special inspections are necessary.

Option 4: Develop TIDs that can be read remotely

Addresses Needs 1, 8, 9, and 17

Development of TIDs that can be applied easily and read remotely will increase the utility of this important component of safeguards.

Option 5: Develop technologies that can detect changes in facilities

Addresses Need 2

Design verification and reverification is critical at reprocessing plants because there are numerous locations where highly attractive material can potentially be diverted with minor modifications to handling equipment. Technologies that quickly and unobtrusively detect changes in equipment would be very useful. Technology needs can be further refined through system studies identified above.

Option 6: Develop better means to authenticate branched and logged operator data.

Addresses Needs 3, 8, 9, and 10

Data branched from a facility's operations computer can ease the burden of audits during an inspection. However, branched data can be falsified either by modifying the branched data or branching from simulation programs. The safeguards community could develop improved means to protect against falsification of these data.

Option 7: Use neutron activation to quantitatively measure waste streams.

Addresses Needs 4 and 7

Improve and tailor delayed neutron measurement technologies to reduce the chances that nuclear materials are diverted through hard-to-measure waste streams.

Option 8: Improve algorithms for acquiring and correcting gamma-ray data for fission product backgrounds.

Addresses Needs 4, 5, 7, and 8

Improvement in quantifying the input accountability value for reprocessing plants will provide a corresponding improvement in the overall inventory difference for accurately declared operations, making it more difficult to mask diversion as a measurement bias.

Option 9: Develop image processing algorithms to detect design changes and material transfers.

Addresses Needs 2, 6, 9, 10, 17, and 18

Image processing techniques can provide simple change detection. Improvement in the algorithms to permit slightly different camera angles between inspections or to permit comparison with electronic architecture drawings will significantly enhance design verification and reverification. This technology may also be useful in monitoring material transfers if the system can be trained to recognize movement of specific geometric shapes such as storage containers without flagging movement of people.

Option 10: Establish a rapid response team of reprocessing and materials control and accounting experts for special inspections.

Addresses Needs 12 and 14

After a special inspection is triggered, an established rapid response team would provide the capability to make observations and measurements before questionable activities could be covered up.

Option 11: Use environmental monitoring to detect reprocessing signatures.

Addresses Needs 15, 16, and 18

Environmental monitoring can provide a sensitive method for detecting reprocessing signatures. This is particularly the case when detection is based on identifying materials that do not exist in nature (e.g., short-half-lived isotopes or materials with unnatural isotopic compositions) and chemicals that have no legitimate industrial purpose.

Option 12: Provide inspectors with observational training to detect inconsistent equipment.

Addresses Needs 11 and 13

Observations of equipment and processes can provide a quantity of information that cannot be obtained in any other way. Operational constraints (available inspection time) and intrusiveness concerns may prevent detailed measurements of many areas within a facility. However, trained observers may be able to detect plant processes or equipment that are inconsistent with legitimate operations. Observations may also provide a basis for directing inspection efforts at specific areas of concern, further optimizing the effort.

Option 13: Develop easily accessible data base to improve information handling.

Addresses Needs 9 and 10

Information handling capabilities being developed today will substantially enhance the ability to access and use different information sources. The ability to compare information from dissimilar sources can assist in resolving apparent discrepancies between expected and actual operations while inspectors are at the site. On-site conflict resolution improves inspection efficiency. In the event of a confirmed inconsistency, having inspectors on site provides the additional benefit that they can monitor for suspicious changes while a response is developed.

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CHAPTER 7

URANIUM ENRICHMENT FACILITIES

I. INTRODUCTION

Increasing the ^{235}U concentration in uranium is the first step in producing materials that can be used for manufacturing nuclear weapons. Most large uranium enrichment plants in operation today were designed to produce LEU for use in power reactors. Diversion of this LEU to reactors for production of plutonium is a potential pathway for acquiring nuclear material for nuclear weapons. Uranium enrichment processes can also produce HEU that can be used directly in the manufacture of nuclear weapons. Thus, application of safeguards at uranium enrichment plants is an important objective of the IAEA international safeguards program.

Two types of enriched uranium have been defined to distinguish between material that can be used directly in nuclear weapons and material that is not directly useful for weapons. Uranium enriched to greater than 20% ^{235}U is defined as HEU and material enriched to less than 20% ^{235}U is defined as LEU. Although LEU cannot be used directly to produce nuclear weapons, when used as reactor fuel, the LEU results in production of plutonium in the irradiated fuel elements. Thus, when considering acquisition of nuclear materials by use of uranium enrichment facilities, two very different pathways must be addressed: direct production of HEU in the enrichment facility and diversion of LEU to a reactor for production of plutonium or to a clandestine enrichment plant for production of HEU for weapons purposes.

The IAEA currently implements safeguards inspection procedures at uranium enrichment facilities that use gas centrifuges and advanced vortex tube isotope separation technologies. These safeguards inspections are based on the traditional approach of material balance verification supplemented by techniques for detecting HEU production. Recent activities have increased interest in implementing international safeguards capabilities for detecting undeclared uranium enrichment facilities in full-scope states. This study considers both current and future safeguards needs for uranium enrichment facilities. The discussion includes options for enhanced verification activities based on detecting HEU production at an LEU facility, verifying LEU quantities produced, and detecting undeclared enrichment facilities.

A. Pathway Description and Safeguards Approaches

The concentration of the ^{235}U isotope in uranium can be increased by several different isotope separation technologies. The technologies that have been used in large-scale facilities and pilot plant operations or research and development efforts are listed in Table 7-I. Other technologies, such as plasma and thermal diffusion, are of theoretical interest.

Table 7-I. Uranium Enrichment Processes in Commercial Use or the Subject of Research and Development Activities

- Electromagnetic Isotope Separation (EMIS)
- Gaseous Diffusion
- Gas Centrifuge
- Jet Nozzle/Vortex Tube
- Molecular Laser Isotope Separation (MLIS)
- Atomic Vapor Laser Isotope Separation (AVLIS)
- Chemical Exchange (CHEMEX)
- Ion Exchange

To date, four of these technologies—EMIS, gaseous diffusion, vortex tube, and gas centrifuge—have been used to produce HEU in sufficient quantities for use in nuclear weapons. The EMIS process was used to produce the first HEU in the US. Until the discoveries in Iraq, the EMIS process was considered only of historical interest from a proliferation viewpoint. The vortex tube process was used to produce a limited quantity of HEU for prototype nuclear weapons in South Africa. The South African HEU plant ceased operation in 1990 and has been partly disassembled. South Africa operates an LEU plant based on advanced vortex tube processes. All large-scale uranium enrichment facilities currently in operation are based on gaseous diffusion or gas centrifuge separation technology. However, HEU could be produced, in quantities sufficient to fabricate a nuclear weapon, in small-scale facilities using any one of the technologies listed in Table 7-I. Pilot plant enrichment facilities have operated, with varying degrees of success, using the jet nozzle, MLIS, AVLIS, CHEMEX, and ion exchange technologies. Production of HEU by declared facilities using low-enrichment gas centrifuges has been a primary safeguards concern; international safeguards approaches have been defined and are being applied to these facilities. The safeguards approaches being implemented are intended to detect diversion of LEU, which could be used as feed for undeclared facilities, or unauthorized production of HEU in declared facilities. A primary technique for detecting undeclared enriched uranium facilities is environmental monitoring to detect unnatural uranium isotopic compositions.

B. Pathway Scenarios

Nuclear materials can be acquired for weapons production through uranium enrichment activities on two materials: HEU produced directly by enrichment plants and LEU placed in reactors to produce plutonium. To help clarify the safeguards concerns and objectives at uranium enrichment facilities, two cases will be addressed: Case I, unauthorized activities at declared enrichment facilities, and Case II, production of enriched uranium at an undeclared enrichment facility. For Case I, three major pathways to proliferation will be addressed: (1) undeclared production of HEU, (2) excess production of LEU, and (3) diversion of declared enriched uranium. For Case II, undeclared enrichment facilities, it is assumed that the purpose for the undeclared facility would be to produce HEU for direct use in nuclear weapons.

An additional pathway for proliferation that could be considered under Case I is the authorized production of HEU for use in research reactors or, potentially, nuclear reactors used for propulsion of naval vessels. Although limited examples do exist for this pathway, the safeguards approaches and options would be similar to those for excess production of LEU at an enrichment facility; therefore, this pathway will not be covered separately in detail in this study.

All large-scale LEU enrichment facilities currently in operation are based on gaseous diffusion or gas centrifuge separation technology. Although other technologies, such as laser isotope separation, could be used in future plants, the discussion here will concentrate on the two technologies currently in use. Pathways to acquisition would be similar for other enrichment technologies and the safeguards needs would also be similar.

1. CASE I—Unauthorized Activities at Declared Enrichment Facilities. The unauthorized activities of concern are enriching uranium beyond authorized levels and diversion of declared materials. These activities have different proliferation indicators and will be discussed separately.

The primary concerns in addressing the issue of enriching nuclear material beyond declared levels are (1) the production of material at an enrichment greater than declared, specifically the production of HEU, and (2) the production of material at declared enrichments at a rate greater than declared.

The first pathway addressed is the production of HEU. The fundamental question is whether the enrichment plant can be operated to redirect separative work units (SWUs) from the production of relatively large quantities of LEU (e.g., 3%) to production of much smaller quantities of HEU. The process parameters that are relevant for determining the capability of an enrichment process for producing HEU include the separation factor, throughput, in-process inventory, and equilibrium time.

The *separation factor* determines the number of stages that must be connected in series to achieve the desired ^{235}U concentration.

The *throughput* determines the number of separation units that must be connected in parallel to provide the desired flow rate.

The *in-process inventory* is the amount of process material that must be introduced into the cascade before enriching operations can begin.

The *equilibrium time* is the time required for the cascade to reach steady-state conditions under which product material can be withdrawn.

The ideal enrichment process for unauthorized production of HEU would have a high separation factor and high throughput so that fewer separation units would be required to achieve the desired product concentration and flow rate. It would have a small cascade inventory so that a minimum in-process inventory would be required to fill the cascade and a short equilibrium time so that the concentration of product material would quickly reach the desired concentration.

In addition, the plant would be designed with a large number of cascades connected in parallel so that one or more cascades could be misused without having to misuse the entire plant. The greater the number of cascades connected in parallel, the greater the possibility that a cascade could be isolated and operated without detection.

Table 7-II compares different technologies for the uranium enrichment process in terms of their capability to produce HEU. Gas centrifuge has a relatively large separation factor; less than 60 stages are required to produce HEU from natural uranium feed. However, because of the low throughput of a gas centrifuge, up to hundreds of centrifuges are required to support HEU production. The equilibrium time is short; only hours are required before HEU product can be withdrawn from a cascade. Because of the low operating pressures, the gas centrifuge process only requires approximately 5 kg of uranium to fill a 10 000 SWU/year cascade. Gaseous diffusion, on the other hand, requires many stages for HEU production (≈4000). Because of the high throughput and large equipment size, in-process inventories are much larger and equilibrium times are long (months for HEU production). The aerodynamic separation processes require many stages and equipment units for HEU production (comparable to gaseous diffusion), but the equilibrium times are relatively short and the inventory requirements are relatively small.

TABLE 7-II. The Processes Compared

Enrichment Process	Separation Factor	Number of Stages[a]	Number of Equipment Units	Equilibrium Time
Gaseous diffusion	1.004	3500–4000	3500–4000	Months
Gas centrifuge	1–2	<60	Hundreds	Hours
Aerodynamic				
– Vortex tube	1.03	Thousands	Hundreds	Days
– Separation nozzle	1.015	2500–3000	2500–3000	Days
Chemical exchange	1.0026	5000–6000	10s of columns	>150 days
Ion exchange	1.001	12 000–16 000	10s of columns	20–90 days
Laser				
– Molecular	2–6	<4	<4	Very short
– Atomic vapor	2–6	<4	<4	Very short
EMIS	~30	2	Thousands	5-15 days

[a] Approximate number of stages and equipment units for plants designed for HEU production.

The HEU production method selected by a plant operator would depend on the details of the safeguards system at the facility in question and the effort an operator was willing to expend to avoid detection by the inspector. The four general scenarios available to an enrichment plant operator are the following:

1. cascade flow adjustment,
2. cascade reconfiguration,
3. recycling LEU (i.e., batch recycling), and
4. using undeclared separative capacity (e.g., a dedicated, clandestine HEU cascade)

The processes evaluated in this study include gas centrifuge and gaseous diffusion; the first process discussed is gas centrifuge.

a. HEU Production in a Gas Centrifuge Facility. The safeguards-relevant factors that make the gas centrifuge process attractive for HEU production include a large separation factor, a small cascade inventory, a short equilibrium time, and a plant design that uses many cascades connected in parallel. A large separation factor means that fewer stages are required to be connected in series to produce HEU enrichments. A small cascade inventory means that a large amount of material is not required to fill the cascade. A short equilibrium time means that once the cascade(s) is altered, HEU can be withdrawn without a lengthy delay for the concentration gradient to be established. A plant configuration of many parallel casfor the concentration gradient to be established. A plant configuration of many parallel cascades means that it may be possible to isolate one or more cascades for misuse while continuing to produce material at the designed enrichment level.

(1) Cascade Flow Adjustments. The first HEU production scenario described is cascade flow adjustment. Reducing the feed rate to a cascade increases the separation factor, which results in an increased product enrichment level. However, the separative capacity decreases. During the normal start-up of a centrifuge cascade, it is not unusual for the enrichment of the product material to increase to nearly 20% for a short period of time (less than an hour) as the feed rate increases to the design rate. Although the operator can control the cascade flow rates, large quantities of material with higher than declared enrichments cannot be obtained in a short period of time; significant quantities could be produced, however, over a long period of time. Using existing process and support equipment, product enrichments near 10% ^{235}U could be obtained from a cascade designed to produce 3% product material with little or no physical modification.

The enrichment level of the cascade product can also be increased by recycling a portion of the product to a lower section of the cascade. Mixing the product stream with the feed stream increases the isotopic enrichment of the feed stream. Normally, a cascade is optimized to produce maximum separative capacity for a given product and tails concentration, so any variation from these values results in a somewhat less efficient cascade. In practice, these sacrifices are not great as long as concentration variations are not too large. If a cascade operator is willing to accept more serious losses in efficiency and a low production rate, the product assay can be increased substantially. Product enrichments of slightly more than 10% ^{235}U can be obtained from a cascade designed to produce 3% product by internally recycling product flows. This scenario also uses existing process and support equipment with little or no physical modification.

The indicators associated with the production of HEU through cascade flow adjustment are listed in Table 7-III.

(2) Cascade Reconfiguration. In cascade reconfiguration, higher than declared enrichments are achieved by changing the process piping such that stages designed to be operated in parallel are actually operated in series. Two basic arrangements can be used to reconfigure centrifuge cascades: (1) the process piping within a cascade can be reconfigured to effectively increase the number of stages and thereby increase the product enrichment and (2) cascades can be connected to operate in series (the product of one cascade is introduced as the feed of the next cascade enabling higher product enrichments to be achieved). In both

Table 7-III. HEU Production Indicators for Cascade Flow Adjustment

1. A reduction in plant material throughput that is proportional to the percentage of cascades isolated from the process
2. The presence of portable feed and withdrawal equipment and extracurricular operations inside the cascade area
3. Non-routine cascade valve settings (e.g., valves that are normally closed will be open, valves that are normally open will be closed)
4. The presence of HEU material in containers and in the header pipes of the isolated centrifuge cascades
5. High-radiation levels (neutron and gamma rays) emitted from the piping and containers of HEU

cases, physical modifications to the existing process system are necessary. It is not expected that any commercial centrifuge plant would already be designed with the necessary interconnecting cascade piping to rearrange the cascades in either of these two configurations.

Although gas centrifuge technology varies greatly in complexity and performance, the separation factor achievable in a single gas centrifuge machine is small enough that several machines must be connected in series to produce LEU. More centrifuges connected in series would be required to produce HEU. The throughput of an individual centrifuge is so small that a large number of machines must be connected in parallel at each stage to produce HEU in quantities for weapons. Any centrifuge plant designed for LEU production has a sufficient number of machines to produce HEU if the machines can be reconnected for this purpose.

The ease with which machines can be reconnected depends strongly on plant design. Some centrifuge machines are designed to be maintained, e.g., by replacing the rotor or the machine mountings. Maintenance obviously requires personnel access to the machines and results in routine movement of equipment in the corridors of the cascade hall. Visual access to centrifuge mountings and interior parts may be considered sensitive information and may be restricted for non-plant personnel. Modification of a LEU plant to produce HEU might involve activities such as reconnection of the piping to individual machines or groups of machines and non-routine methods of adding or withdrawing UF_6 from cascade equipment. In plants where machine maintenance is routine, activities associated with production of HEU would have to be distinguished from the routine maintenance activities. Therefore safeguards approaches based on use of surveillance systems are more complex for centrifuge plants that require routine machine maintenance.

In some centrifuge plants, the machines are designed to have an economically useful life expectancy and are not maintained. Failed machines are simply isolated from the operating equipment. Personnel access may not be a routine occurrence in such plants. When there is no routine activity in the cascade area near the centrifuge machines, surveillance safeguards measures may be more useful and effective.

Some centrifuge plant designs have gas manifolds, appropriate valves, and interplant piping so that the relative configurations of groups of centrifuge machines could be changed relatively easily. Gas manifolds are part of the mechanism used to feed and withdraw UF_6 gas from groups of centrifuge machines. Therefore, instrumentation to monitor the configuration of gas manifolds, associated valves, or the enrichment of UF_6 gas may be a useful safeguards measure.

In summary, any gas centrifuge plant of reasonable size contains enough centrifuge machines to be reconfigured for production of HEU. The number of machines needed to produce HEU at a significant rate and the ease with which the reconfiguration could be accomplished, concealed, or detected depends heavily on plant and machine design. The safeguards approach must take into consideration the specific plant design features.

The major indicators associated with the production of HEU through cascade reconfiguration are listed in Table 7-IV.

Table 7-IV. HEU Production Indicators by Cascade Reconfiguration

1. Reduced plant throughput
2. Unauthorized activities in the process areas
3. Additional piping installed
4. The presence of HEU and
5. An increase in radiation levels in the piping

(3) Batch Recycling. In batch recycle, higher than declared enrichments can be achieved by collecting product material from one or more cascades and subsequently feeding the collected material back into the same cascade. In this method, physical modifications to the process and support systems are not necessarily required; an operator could feed and withdraw material by connecting portable equipment to the cascade service connections. A stationary, in-place feed and withdrawal system could be installed within the cascade area to covertly misuse a declared commercial cascade (or a few centrifuges).

It would, of course, be possible to use the entire plant in a batch recycling mode without reconfiguring the cascades. Product material could be introduced as feed material until the desired enrichment was reached. This scenario would be easier to detect because the entire plant would be involved and all process equipment would contain material with higher than authorized enrichments. In addition, no LEU could be produced during the HEU production cycle.

A major indicator of batch recycling would be reduced plant throughput. In a small centrifuge plant, batch recycling would be more difficult to conceal because the isolation of one cascade would represent a large portion of the overall plant throughput. However, in a larger centrifuge plant the throughput of a single cascade would be less significant. The other indicators include unauthorized operating procedures, the presence of HEU, and increased radiation signals in the cascade piping.

(4) Combination. An attractive HEU production scenario would involve a combination of cascade interconnection and batch recycling. In cascade interconnection, the top cascade would be starved of material. In batch recycling, the initial passes require long operating times. Combining these two scenarios takes advantage of the strengths of each while minimizing their weaknesses. Table 7-V summarizes the HEU production scenarios using a reference centrifuge cascade. The reference cascade contains 250 centrifuge machines arranged in six stages: four enriching stages and two stripping stages. The separation factor for each centrifuge is approximately 2, and the cascade has a separative capacity of 10 000 SWU/year.

TABLE 7-V. HEU Production Using the Reference Cascade

Scenario	Minimum Cascades Required	Enrichment Achieved	Production Time for 25 kg 235U[a]	Indicators: Visual[b]	Indicators: Presence of HEU
Flow adjustment	1	≈20%	≈5 years	Valve settings	May be less than HEU for entire production period
Cascade reconfiguration					
Internal reconfiguration	1	≈90%	7.5 months	Extensive stage piping modifications	Top half of cascade for entire production period
Cascade interconnection	3	≈90%	4 months	Header pipe modifications or tubing to service connections	Top two cascades for entire production period
Batch recycle	1	90+% (4 passes)	2.6 years	Valve settings	Passes 3 and 4 for a total of 1 month
Batch recycle/cascade	7	90+% (2 passes)	4.5 months	Valve settings and tubing	Pass 2 for < 1 week

a Assuming minimum number of cascades.
b All scenarios include portable feed and withdrawal equipment and extra cylinders.

Three scenarios enable HEU to be produced by isolating only one cascade: cascade flow adjustment, cascade reconfiguration, and batch recycling. Material enriched to 90% or greater can be achieved in each scenario except cascade flow adjustment. The time required to produce 25 kg of ^{235}U ranges from 4 months to approximately 5 years. All scenarios would involve the use of portable feed and withdrawal systems and would require the presence of extra cylinders. The effect on the plant throughput is proportional to the number of cascades isolated from the process system. Internal reconfiguration of the cascade requires the most modifications and would be the easiest to detect visually. The batch/recycle interconnection combination requires HEU to be present for the shortest period of time.

(5) Undeclared Separative Capacity. In a centrifuge plant the operator could utilize undeclared separative capacity in several manners. If the inspectors were not permitted inside the process building after the initial safeguards design verification, the plant operator could add an additional cascade. This cascade could then be used to batch-recycle material over a long period of time. Similarly, it would be difficult for the inspector to independently verify, in cascades where centrifuges may have been replaced, whether the replaced centrifuges actually have the separative capacity declared by the operator. If the plant is in an upgrade phase, the operator could misinform the inspector of the cascade startup schedule. Using a combination of batch recycling and cascade interconnection, the operator could produce a significant quantity of material if a production unit was in operation five months ahead of schedule.

These concerns have contributed to the choice of the "limited frequency unannounced access" safeguards approach for commercial gas centrifuge plants to verify the absence of HEU production with cascade hall inspections and to verify the absence of LEU diversion with nuclear material accountancy.

b. HEU Production in a Gaseous Diffusion Facility. The following process parameters make gaseous diffusion less attractive than gas centrifuge for unauthorized HEU production. Gaseous diffusion processes have a much smaller separation factor, which means that many more enriching stages must be used to produce HEU. Several thousand stages are required to produce HEU from natural uranium. The process has a larger in-process inventory, which means that more material is required to initiate HEU production scenarios. The equilibrium time is longer; therefore, the production cycle for HEU will run longer. Finally, plants designed for using gaseous diffusion are usually one-cascade plants, which means the entire plant must be misused during the HEU production scenario.

(1) Cascade Flow Adjustment. Higher enrichments can be achieved by reducing the feed rate and recycling a portion of the product stream. Because of the longer time required to establish the gradient, the gaseous diffusion process would require longer delays between the start of undeclared operations and the withdrawal of product material. In addition, the product flow at the designed enrichment would have to cease during the unauthorized operation.

(2) Cascade Reconfiguration. The cascade reconfiguration scenario is not applicable for gaseous diffusion processes. Each stage is constructed as a single piece of process equipment and the stage piping cannot be reconfigured to change the number of equipment units connected in parallel within a stage to increase the total number of stages. Also, a plant is typically built as a single cascade and the cascade piping cannot be reconfigured to connect multiple cascades in series.

(3) Batch Recycle. The batch recycling scenario would be essentially the same for all types of enrichment processes. The primary difference is that gaseous diffusion requires longer equilibrium times and larger inventories to fill the cascade. In addition, the entire plant must be misused and the normal product stream must be completely stopped during unauthorized operation.

(4) Criticality Considerations. In a gaseous diffusion plant, nuclear criticality is a concern associated with production of HEU in a facility designed for LEU production. Nuclear critically is not normally a concern in gas centrifuge plants due to the low gas pressure and resulting low quantity of material present in the process equipment. Criticality can be a concern in a gaseous diffusion plant if the enrichment exceeds the design enrichment due to the higher pressures and larger volumes of the process equipment. Gaseous diffusion plants designed for HEU production would have smaller equipment such as pumps, UF_6 traps, and product withdrawal vessels. The presence of the smaller equipment could serve as visual indicators of HEU production capability.

c. Summary of HEU Production Pathways. In gaseous diffusion plants designed for LEU production, production of HEU would require extensive design changes, due to critically considerations, and extensive changes in operating characteristics of the facility. Design verification activities at the facility prior to operation and visual inspections during safeguards inspections could detect HEU capability. Therefore, production of HEU at a gaseous diffusion facility under safeguards is not considered a likely pathway for proliferation. In uranium enrichment facilities using gas centrifuge as the separation technology, the concentration of the UF_6 gas is very low, criticality is not a concern, and HEU production can begin in a few hours by reconfiguring cascade piping connections. Thus, detection of HEU production at LEU facilities using gas centrifuge separation technology is a high-priority safeguards objective. IAEA safeguards for detection of HEU production at gas centrifuge plants currently rely on unannounced access to the cascades for visual observation and measurements of process gas enrichment at cascade header pipe locations.

d. Production of Excess Product. Production of excess enriched uranium at the authorized enrichment level also provides a proliferation pathway and must be considered in designing safeguards systems for LEU production facilities. The excess material could be produced by redirecting a portion of the plant's separative capacity to enrich undeclared feed materials. This undeclared activity is difficult to detect because the inspector does not have a method to verify the separative capacity of the plant. The operation cannot be detected by examining the material accountability data because neither the extra feed material nor the excess product would be entered into the records. In addition, many of the indicators present during HEU production (e.g., piping changes, valve settings, radiation signatures) are not applicable because the plant is operated to produce material at the declared enrichment level.

Potential indicators of excess product include the presence of excess UF_6 cylinders in the feed or withdrawal areas and in the process areas of the plant, an inventory difference (assuming excess tails material is not removed), and a declared plant throughput less than the designed maximum throughput rate.

Potential scenarios for concealing production of excess product include understating the material throughput, understating the separative capacity of the plant, and increasing the separative capacity after startup. These scenarios are difficult to detect because of the difficulty in independently verifying the separative capacity of a plant.

e. Summary of Proliferation Pathways. The primary proliferation pathway for gas centrifuge plants is the production of HEU. The factors that make HEU production plausible in gas centrifuge facilities include the ability to isolate cascades, the ability to feed and withdraw material inside the process areas, the small in-process inventory, and the short equilibrium time. These factors make batch recycling especially attractive. The operator's choice of production method would be determined by consideration of cascade design, production goals, and probability of detection. The key indicators of possible HEU production are listed in Table 7-VI.

TABLE 7-VI. Key Indicators of HEU Production

1. Reduced plant throughput
2. Presence of portable feed and withdrawal equipment
3. Extra UF_6 cylinders in the process area
4. Changes in valve settings
5. Piping reconfiguration
6. Higher radiation levels in piping and process equipment

The production of excess LEU is also plausible and is difficult to detect because of the difficulty in verifying the plant's true separative capacity.

In gaseous diffusion plants, undeclared production of HEU is much more difficult to conceal because diffusion plants are constructed as a single cascade and the entire plant must be misused. Production of excess LEU is plausible and difficult to detect. An additional factor that makes excess production difficult to detect in a gaseous diffusion facility is the large in-process inventory that can be 10-30% of the plant throughput. Possible indicators of excess production are listed in Table 7-VII.

TABLE 7-VII. Potential Indicators of Excess LEU Production

1. Reduced declared throughput
2. Unauthorized feed and withdrawal activities
3. Extra UF_6 cylinders in the feed and process areas

2. CASE II—Undeclared Uranium Enrichment Facilities. In this study it is assumed that the purpose of an undeclared uranium enrichment plant would be to produce HEU for direct use in weapons production. A primary technique under consideration for detection of undeclared enriched uranium facilities is environmental monitoring to detect the signature of isotopically altered uranium.

Uranium enrichment facilities inevitably leave a unique signature in the environment in the form of isotopically altered uranium, which can be detected in samples of soil, vegetation, or water using sensitive analytical techniques. All current large-scale uranium enrichment facilities use gaseous diffusion or gas centrifuge as the separation technology. These facilities use UF_6 gas in the separation process. Facilities using the vortex tube or jet nozzle separation technology also use gaseous UF_6 as a separation medium. All of these facilities typically use purge gases during operation to remove UF_6 from process equipment. The purge gases pass through several stages of cold traps and chemical traps before being released to the atmosphere to prevent release of uranium-bearing material to the environment. However, some small fraction of the UF_6 inevitably escapes in the gas phase. UF_6 reacts immediately with water upon release to the atmosphere to form UO_2F_2. The UO_2F_2 coalesces around dust particles in the air. The particles grow larger with time and eventually fall from the atmosphere and enter the environment in the vicinity of the enrichment facility. Uranium released from these purging processes will generally have an altered isotopic content, leaving a unique signature of the presence of activities involving enriched uranium.

Other separation technologies that do not use gaseous UF_6 as a process medium may have different release materials and pathways to the environment. Facilities using the electromagnetic enrichment technology would typically use UCl_4 as a source of uranium. This compound is volatile (melting point 690°C) and reacts with water on exposure to the air. Thus, some release of uranium-bearing compounds into the air, either as gas phase molecules or fine particles, would be expected. Uranium isotopic separation processes based on ion-exchange, chemical extraction, or laser excitation techniques would be expected to release different forms of uranium through the ventilation and waste water effluents from the facility.

Regardless of the chemical form reaching the environment, the presence of isotopically altered uranium in a state with no declared uranium enrichment or enriched uranium processing facilities would provide an unambiguous rationale for "special inspections" or other steps by the IAEA to resolve the inconsistency.

In cases where uranium enrichment activities have been detected, further examination of samples for the presence of other elements, alloys, or materials could be used as secondary signatures to ascertain the type of uranium enrichment activities present. For example, in facilities using corrosive UF_6 gas, special alloys are required for construction of equipment exposed to it. In the gaseous diffusion process, the diffusion barrier is fabricated from special materials, e.g., nickel powder. The presence of any of these materials in the environment at a suspect site could increase the IAEA's capability to detect undeclared uranium processing activities.

Analysis of samples taken in the vicinity of large uranium enrichment facilities for uranium isotopic content demonstrates that enrichment facilities using gaseous UF_6 can be detected at distances of several kilometers from the site. Additional data from other facilities are needed to reach a conclusion concerning the probability of detecting small facilities producing HEU.

II. OBJECTIVES

Safeguards objectives for uranium enrichment plants will be addressed in this study for the following two cases: Case I, detection of undeclared activities at declared uranium enrichment facilities for production of LEU, and Case II, detection of undeclared uranium enrichment facilities. These objectives are shown in Table 7-VIII.

TABLE 7-VIII. Objectives for Safeguarding Uranium Enrichment

	CASE I—Undeclared Activities at Declared Enrichment Facilities
Objective 1	Detection of the production of enriched uranium with enrichments higher than declared (HEU production),
Objective 2	Detection of the production of excess or undeclared uranium at the declared enrichment, and
Objective 3	Detection of the diversion of a significant quantity of declared uranium in the form of LEU.
	CASE II—Undeclared Uranium Enrichment Facilities
Objective 4	Detection of an undeclared uranium enrichment facility at a declared nuclear site and
Objective 5	Detection of an undeclared uranium enrichment facility at an unknown site.

A. Case I—Undeclared Activities at Declared Enrichment Facilities

Meeting the safeguards objective at an LEU enrichment plant must take into account the unique capability of this type of facility to produce HEU suitable for use in nuclear weapons. As applied to gas centrifuge enrichment plants, implementation of the objective of safeguards entails a set of safeguards measures whose application by the inspectors permits them to detect in a timely manner and with high confidence the diversion of material from declared plant flows or the undeclared production of material.

The diversion of LEU is important because diverted material could be used as feed to enrichment equipment for undeclared HEU production or as undeclared fuel in a nuclear reactor to produce plutonium having potential use in a nuclear weapons program. The undeclared production of HEU is a high-priority objective because of the potential for its direct use in a nuclear weapons program.

B. Case II—Undeclared Uranium Enrichment Facilities

As stated earlier, in this study it is assumed that the purpose of an undeclared uranium enrichment plant would be to produce HEU for use in weapons. The safeguards objective would be to detect such an activity at its earliest stages, preferably in the design or construction stage prior to actual production of material. It is possible that such an activity could take place at a declared nuclear facility.

An undeclared uranium enrichment facility at an unknown site could be detected by analyzing environmental samples taken from a suspect site for isotopically altered uranium. Detection of an undeclared enrichment facility at a declared nuclear site may be complicated by the presence of enriched uranium and nuclear processing equipment needed for site activities. For example, enriched uranium and equipment or materials (LEU, UF_6 cylinders) would be present at a fuel fabrication facility and may have signatures similar to some of those expected from uranium enrichment activities. In addition to these signatures, information concerning export of equipment and materials with signatures related to uranium enrichment plants could be useful in identifying suspect sites.

III. NEEDS

Safeguards needs for uranium enrichment plants will be addressed in this study for the following two cases: Case I, detection of unauthorized activities at declared uranium enrichment facilities for production of LEU, and Case II, detection of undeclared uranium enrichment facilities. The needs addressing the objectives for Case I and Case II are listed in Table 7-IX.

A. Case I—Unauthorized Activities at Declared Enrichment Facilities

Need 1: Continuous monitoring to verify that HEU has not been produced
Need 2: In-line monitors to verify HEU in header pipes
Need 3: Environmental sampling in and near the plant
Need 4: Verification of cascade configuration changes

TABLE 7-IX. Needs for Enhanced Safeguards for Uranium Enrichment Facilities

	CASE I—Unauthorized Activities at Declared Facilities
Need 1	Continuous monitoring to verify that HEU has not been produced since the last inspection
Need 2	In-line monitors to verify UF_6 in header pipes
Need 3	Environmental sampling in and near the plant
Need 4	Verification of cascade configuration changes
Need 5	Advanced techniques for verification of UF_6 cylinders
Need 6	Verification of separative capacity
Need 7	Verification of plant throughput
Need 8	Design verification procedures for operating facilities
	CASE II—Undeclared Uranium Enrichment Facilities
Need 9	Techniques to detect presence of enriched uranium above authorized limits
Need 10	Environmental monitoring techniques to detect uranium enrichment facilities
Need 11	Advanced information systems to provide data related to suspect sites
Need 12	Safeguards approaches for new enrichment technologies

Needs 1 through 4 address the objective of detecting the production of enriched uranium with enrichments higher than declared (HEU production). Development of a technique for continuously monitoring (Need 1) the process equipment or cascade piping for signatures indicating HEU production would greatly increase the effectiveness of safeguards at gas centrifuge enrichment plants. The monitors could be for neutrons or gamma rays. Recent developments in low-cost gamma detectors could be useful in this application. In-line monitors for header pipes (Need 2) could also provide data indicating absence of HEU. Analysis of swipe samples from selected areas (e.g., product withdrawal) in the process or near the site (Need 3) could provide evidence of any HEU production over an extended period of time. Techniques to verify cascade piping changes (Need 4) could be useful in gas centrifuge plants to detect configurations permitting HEU production in isolated cascades.

Need 5: Verification of UF_6 cylinders

Need 6: Verification of separative capacity

Need 7: Verification of plant throughput

Needs 5 through 7 address production of excess material at the authorized enrichment. Advanced techniques for verification of UF_6 cylinders (Need 5) are required to ensure that all cylinders and the total quantity of LEU produced are accounted for during inspections and in periods between inspections. A technique for independently verifying the separative capacity (Need 6) is required to provide a means of ensuring that excess LEU production could be detected. A procedure for verification of plant throughput (Need 7) would also permit detection of excess production of LEU. The detection of LEU diversion should also be addressed by advanced techniques for verification of UF_6 cylinders (Need 5). Verification in this sense would include verifying that all cylinders were accounted for and all shipments of product were recorded in the accountability records.

Need 8: Design verification procedures for operating facilities

Need 8, design verification procedures, addresses both detection of excess material production and detection of LEU diversion. Knowledge of the separative capacity of the plant gained through design verification would provide information on plant throughput and allow comparisons of declared production rates with designed capacity.

B. Case II—Undeclared Uranium Enrichment facilities

Need 9: Techniques to detect presence of enriched uranium above undeclared levels

Need 9 addresses detection of a uranium enrichment facility at a declared nuclear site. A site processing UF_6 as LEU material could conceivably have a clandestine enrichment facility on site. The LEU on-site could be used to produce HEU in the hidden facility. Detection of the presence of uranium enriched above authorized limits would indicate undeclared activities at the site. These techniques could consist of NDA measurements of process equipment or analysis of environmental samples taken in the process and near the site or both.

Need 10: Environmental monitoring techniques to detect uranium enrichment facilities

Need 11: Advanced information systems to provide data related to suspect sites

Need 12: Development of safeguards approaches for new enrichment technologies

Needs 10 through 12 address detection of undeclared enrichment facilities at unknown sites. Environmental monitoring techniques applied both wide scale and near suspect sites offer one of the most promising solutions to the problem of detecting undeclared nuclear facilities of any type. Advanced information systems can supply data useful for locating suspect sites by assimilating information concerning material exports related to uranium enrichment facilities. Development of safeguards approaches for new enrichment technologies is essential to detection of undeclared facilities using these technologies. The signatures of the process must be identified before detection techniques for safeguards can be evaluated.

IV. OPTIONS

The safeguards options for addressing the needs identified are listed in Tables 7-X and 7-XI. In discussing safeguards options to meet the identified needs, overlap will occur, as some options fulfill more than one need. The options are described and their relationships to the needs are noted by number unless a detailed explanation is required.

Option 1: Development of safeguards approaches for advanced enrichment technologies.

Addresses Need 12

Development of safeguards approaches for advanced enrichment technologies is essential as these technologies mature and approach the construction stage. The signatures of different technologies, possible scenarios for production of HEU, and diversion of LEU should be a prime consideration in evaluating these technologies during the research and development stages.

Option 2: Systems studies to identify advanced safeguards approaches for uranium enrichment facilities.

Addresses needs in general

TABLE 7-X. Options for Enhanced Safeguards for Uranium Enrichment Facilities

CASE I—Unauthorized Activities at Declared Facilities

System Studies	
Option 1	Development of safeguards approaches for advanced enrichment technologies
Option 2	Systems studies to identify advanced safeguards approaches for uranium enrichment facilities
Inspection Procedures	
Option 3	Develop design verification procedures (verification of separative work capacity)
Option 4	Develop environmental sampling procedures for unauthorized enrichment at declared facilities
Equipment and Instrumentation	
Option 5	Continuous on-line monitors to detect HEU production
Option 6	Advanced NDA measurement techniques for UF_6 cylinders
Option 7	Advanced seals for UF_6 cylinders
Option 8	Verification of UF_6 cylinder tare weights
Option 9	Advanced techniques for ^{235}U enrichment measurements
Option 10	Advanced digital surveillance systems
Option 11	Remote monitoring systems for safeguards equipment
Training	
Option 12	Observational training
Information Systems	
Option 13	Advanced information systems with data on plant operating characteristics

Option 3: Develop design verification procedures.

Addresses Needs 1, 4, 6, and 7

Design verification procedures are essential to gaining the knowledge necessary to verify the separative work capacity of a plant and understand plant operating parameters sufficiently to detect changes that could be made to produce HEU or excess LEU.

TABLE 7-XI. Options for Enhanced Safeguards for Uranium Enrichment Facilities

CASE II—Undeclared Uranium Enrichment Facilities

System Studies	
Option 1	Development of safeguards approaches for advanced enrichment technologies
Option 2	Systems studies to identify advanced safeguards approaches for uranium enrichment facilities
Inspection Procedures	
Option 14	Develop environmental sampling and analysis procedures for suspect sites
Equipment and Instrumentation	
Option 15	Portable instrumentation for analysis of uranium in environmental samples
Option 16	Enhancement of mass spectrometry procedures for analysis of environmental samples
Option 17	Monitoring power lines for signals typical of enrichment plant equipment
Training	
Option 18	Training in environmental sampling techniques
Information Systems	
Option 19	Develop advanced information systems with data related to characteristics from suspect plant sites

Option 4: Develop environmental sampling procedures for unauthorized enrichment at declared facilities.

Addresses Need 3

Analysis of samples taken in or near an enrichment facility could be useful in detecting production of HEU at the facility. Additional data are required to evaluate the usefulness of this technique.

Option 5: Continuous on-line monitors to detect HEU production.

Addresses Needs 1 and 2

Continuous on-line monitors to detect HEU production could result in the more reliable and efficient application of safeguards in gas centrifuge enrichment plants. The monitors could be designed for either gamma rays or neutrons. Recent developments in low-cost, rugged gamma-ray detectors have potential applications in this area.

Option 6: Advanced NDA measurement techniques for UF_6 cylinders.

Addresses Needs 5 and 7

The current NDA measurement techniques measure only the uranium on or near the wall of the UF_6 cylinder and are not accurate for tails and feed material. The bulk of the material in these cylinders is never directly measured. It is desirable to be able to verify both the total uranium and ^{235}U content of the cylinders. One option is to count active neutrons from the cylinders. This technique is expensive and requires extensive equipment development. Another option is to use advanced gamma-ray measurements, using high-energy daughter peaks, to verify material in the cylinder and advanced spectral analysis techniques to verify wall thickness measurements.

Option 7: Advanced seals for UF_6 cylinders.

Addresses Needs 5 and 7

The verification of UF_6 cylinders by measurement is time consuming and intrusive. New seal technology combined with other surveillance measures could result in a continuous knowledge of filling and weighing UF_6 cylinders, provide sufficient verification, and improve the efficiency and reliability of safeguards.

Option 8: Develop a method for verifying tare weights of UF_6 cylinders.

Addresses Needs 5 and 7

Inspectors have difficulty in establishing tare weights for UF_6 cylinders. A system for positively identifying UF_6 cylinders, remotely monitoring the weighing, and authenticating and recording the data could address this need.

Option 9: Advanced techniques for ^{235}U enrichment measurements.

Addresses Needs 2 and 5

Current procedures for ^{235}U enrichment measurements require knowledge of the container wall thickness and calibration with standards similar to the material. Advanced techniques for analyzing gamma spectra could provide more reliable and efficient procedures for these measurements.

Option 10: Advanced digital surveillance systems.

Addresses Needs 4, 6, 7, and 8

One of the safeguards measures currently used to verify the absence of HEU production in gas centrifuge facilities is visual inspection of the cascade piping. This inspection is difficult to accomplish reliably. Advanced digital surveillance techniques could compare images from inspection to inspection and result in a more reliable safeguards inspection. The technology could also provide remote monitoring capability.

Option 11: Remote monitoring systems for safeguards equipment.

Addresses Needs 1, 4, 5, and 7

The difficulty in detecting excess production and diversion of LEU at enrichment plants could be addressed by positive verification of the quantity of material withdrawn from the product station and loaded into UF_6 cylinders. This option would use remote monitoring of the production withdrawal station; the system would include load cells, UF_6 cylinder identification systems, enrichment measurements, and camera surveillance interfaced to the IAEA safeguards computer system. The computer data could be authenticated and used to assure that all product taken from the withdrawal station was measured and that results were recorded for use by inspectors or remote monitoring stations.

Option 12: Observational training.

Addresses Needs 4, 6, and 8

Safeguards inspections can be enhanced by increasing inspector awareness of proliferation indicators concerning changes in plant operating conditions or modifications that may be overlooked in normal routine inspections.

Option 13: Advanced information systems for safeguards data.

Addresses Needs 7, 8, and 12

Advanced safeguards information systems can provide data on plant operating parameters (e.g., shipments, planned production schedules, and modifications to equipment) that would increase the reliability of safeguards inspections at declared facilities and aid in identifying suspect facilities that may have undeclared enrichment operations.

Option 14: Develop environmental sampling procedures for suspect sites.

Addresses Needs 1, 2, and 10

Analysis of environmental samples is a promising technique for detecting undeclared enrichment facilities. Additional data from representative facilities are necessary to evaluate the capability of the technology.

Option 15: Portable instrumentation for analysis of uranium in environmental samples.

Addresses Needs 2, 9, and 10

Portable instrumentation for analyzing environmental samples on-site could be a powerful tool for detecting undeclared enrichment facilities. Portable instruments are feasible and additional resources are required to develop a prototype field instrument.

Option 16: Enhancement of mass spectrometry procedures for analysis of environmental samples.

Addresses Needs 9 and 10

The sensitivity with which enriched uranium can be detected in environmental samples depends on the precision of the mass spectrometers used to analyze the isotopic ratios. Techniques for improving the precision have been tested and procedures are required for applying the techniques to commercial mass spectrometers available at the IAEA laboratory in Seibersdorf.

Option 17: Monitoring power lines for signals typical of enrichment plant equipment.

Addresses Need 9

Gas centrifuges have unique electrical signatures that may provide a means of remotely monitoring suspect sites for operation of a gas centrifuge enrichment facility. Equipment is being developed and signatures of centrifuges are being collected for analysis.

Option 18: Training in environmental sampling techniques.

Addresses Need 10

Selection of sample collection points and materials for collecting and handling environmental samples require detailed procedures. Inspectors need to be trained in these techniques to provide reliable samples.

Option 19: Develop advanced information systems with data related to suspect plant site characteristics.

Addresses Needs 7, 8, 9, and 12

Advanced safeguards information systems could provide valuable data for planning safeguards inspections at declared enrichment facilities. The data should include planned operating capacity, plant throughput, and any changes or modifications expected at operating facilities. The system could also supply data to aid in identification of suspect sites of undeclared enrichment activities.

New safeguards approaches could potentially provide more efficient and reliable safeguards for all nuclear facilities. These could include use of data from national information systems and remote monitoring systems.

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CHAPTER 8

WEAPONIZATION

I. INTRODUCTION

In the context of this paper, weaponization refers to knowledge, techniques, technologies, and engineering activities required to acquire, construct, and deliver a nuclear explosive device capable of achieving a nuclear yield, presuming that fissile material is available. Weaponization includes the military preparations that are necessary to deliver a weapon at the correct time and place. Intimately tied to weaponization is the development of personnel with the necessary technical skills. In the context of this study, weaponization is restricted to those activities that do <u>not</u> relate to the acquisition, refining, or separation of the fissile material necessary (but not sufficient) to fashion a nuclear bomb. Although the role of nuclear testing in weapons development will be discussed along with the signatures and indicators of preparations for testing, the detection of a nuclear test will not be addressed here.

Traditional international safeguards activities emphasize nuclear material inspections at nuclear facilities declared peaceful. Weaponization activities, by definition, are conducted outside such facilities. Therefore, the detection of such activities in a state indicates the intent of that country to proliferate.

Until recently, weaponization detection was addressed through means such as national and international export control efforts and national technical means. A change in viewpoint occurred following the 1991 Gulf War. In Iraq, the UNSCOM drew on IAEA and outside inspection expertise from member states. Although this may occur again in the future, it may be desirable for the international community to develop a more conventional way to recognize weaponization. However, it should be understood that significant policy questions must be addressed in determining whether and to what extent the IAEA or any other international body should acquire such capabilities. The purpose of this chapter is to delineate the technical possibilities. Any decisions will need to consider a wide range of additional factors.

If it is decided that the IAEA is to be involved in the detection of weaponization, new resources will be required. In addition to financial resources, an important element in such a program is the acquisition of personnel with appropriate technical experience. Another issue is the complication that relates to the releasability of weaponization information to the IAEA; while sufficient information must be provided to ensure that the agency is technically and politically able to detect weaponization, limits are required to prevent information dispersal outside the IAEA.

The rest of this chapter will first discuss some basics of nuclear weapons and then describe the various activities involved in weaponization. This will be followed by sections on the safeguards objectives that might be formulated in connection with weaponization, the needs that these objectives suggest, and a list of the various options for augmenting safeguards activities to detect weaponization. In most of the material described here, it is assumed that a proliferating nation will need to develop the bulk of the necessary technology indigenously. However, it may be possible for a nation to buy much of the necessary technology, including the weapons themselves, on the international market.

A. Weapons Components

A key element of a nuclear weapon is a means of rapidly assembling sufficient fissile material to obtain a supercritical chain reaction. The fission chain reaction begins when a neutron enters a fissile nucleus and destabilizes it, so that it fissions with the production of energy and more neutrons to propagate the chain. The assembly of the fissile material must be rapid enough to obtain the maximum number of fissions before the mass is blown apart by the violence of the chain reaction; assembly is achieved in one of two ways: a gun device or an implosion device.

The minimum mass of material that is necessary to sustain a chain reaction is called a critical mass. The critical mass varies with the type of material, its geometric distribution, its density, and the presence of surrounding material that can reflect neutrons or change their energy. The reflective material, referred to as a tamper, may also act to retard the outward movement of the assembly and thus sustain the chain reaction for a longer time. For a weapon, it is necessary to assemble more that one critical mass and therefore to create a supercritical condition.

A gun device is the simplest method of rapidly assembling two subcritical masses. This involves firing one subcritical piece of fissile material into another subcritical piece of fissile material to create a supercritical mass. Once the supercritical mass has been achieved, an appropriate neutron source can initiate the chain reaction.

An implosion device relies on compression to produce a critical assembly of fissile material. Again, an appropriately designed neutron generator provides the neutrons to initiate the chain reaction. In general, an implosion device is harder to design, but it is more efficient in its use of nuclear material.

The yield of a weapon can be further enhanced through the use of materials composed of atoms that combine (fuse) to produce a heavier atom and large amounts of energy. The high temperatures produced by the explosion of a fission device are sufficient to initiate fusion reactions. This is the basis of boosted and thermonuclear weapons. A common fusion reaction is that between deuterium and tritium. The tritium is produced by the irradiation of lithium-6 (^{6}Li) with neutrons.

In parallel with the design of the nuclear system, a proliferant must develop the capabilities to manufacture the ordnance components of the nuclear explosive device. These include the ability to carefully shape fissile material and high-energy explosives and to design, develop, or otherwise acquire the electronic or mechanical components or both associated with the arming, fusing, and firing system of the weapon.

B. Weaponization Pathway

Although the basic physical principles, as described above, are widely known and relatively straightforward, the activities associated with a weaponization program are typically rather complex and extensive, providing a large number of indicators or signatures that might, in principle, be detected. These indicators in most cases are not definitive. Their detection would not constitute firm evidence or proof of proliferation intent. However, they might, in combination with other information, furnish important clues.

A nuclear weaponization program requires research and technical expertise in a wide range of technical, scientific, and engineering disciplines. Expertise is required in metallurgy, electronics, physics, chemistry, computer science, compressed matter physics, explosives, mechanical engineering, and electrical and nuclear engineering. Therefore, one major concern that a nation embarking on a nuclear weapons program must address is the need for trained scientists, engineers, and technicians. Acquiring or developing the trained, dedicated human resources requires a long-term commitment on the part of the country involved and the individuals who will form the nucleus of a development program. Technical education in the large variety of disciplines mentioned above is required, as are the development or acquisition of laboratory and testing capabilities.

The development of the human infrastructure for a weapon program requires that personnel be employed directly in a clandestine program, in dual use industries, or perhaps in foreign firms to gain experience. Analyses of a country's industrial activities may provide an indication of weaponization, particularly if they are inconsistent with either the technological state of development in the country or of other industrial activities within the country.

The exact nature and extent of a weaponization program depends on the

1) intent of the developer (i.e., is the proliferant intent on developing a single device or a multi-weapon, 20-year, enduring stockpile?);

2) physics design of the nuclear device (implosion or gun-assembled explosive device);
3) safety or reliability concerns;
4) delivery mode (i.e., the means of moving the device by ox cart or missile to the desired detonation location);
5) existing technical, human resource, and industrial infrastructure in the proliferating country; and
6) source, condition, and nature of the fissile material available to the potential proliferant.

For a gun design, activities involved are likely to include high-speed photography to understand the internal ballistics of the system and neutron diagnostics to determine if sufficient neutrons will be available to initiate the weapon. Computational physics models can aid in the selection of design parameters.

The development of implosion weapons is more difficult. Here modern computational physics models can be of significant help. One major activity in the development process is hydrodynamic testing. This involves setting off explosives around mock fissile material to test prototype implosion systems. Among the diagnostic tools used are flash x-ray and high-speed photography. The results of the hydrodynamic testing can be used directly or as a means of calibrating the computational physics models.

In the absence of constraints on testing, the next step in the development of an implosion device would be to detonate test devices to ensure they operate as designed. Based on US experience in the Manhattan Project, it was possible to develop enough confidence in the design of a gun device that testing was not necessary. However, an inability to test would pose a more significant hindrance to the development of an implosion weapon. In the absence of the ability to test, a proliferant is left with two alternatives to increase confidence in a weapon design. The first is to attempt to refine the computational physics models to further increase confidence in the design. However, this is quite difficult without test data. An alternative approach used by the US during the nuclear testing moratorium of the late fifties and early sixties was hydronuclear testing. This was carried out to resolve safety concerns about weapons in the stockpile. Hydronuclear experiments are hydrodynamic tests involving very small amounts of fissile material. These tests result in yields of less than one-thousandth of a pound of high-explosive equivalent.

A proliferant would also need to develop the capability to manufacture weapons. This includes the ability to process and machine fissile material; the ability to machine explosives; and the ability to design, develop, and produce the electronics associated with the firing, fusing, and arming systems. An ability to fabricate the weapon and to acquire or develop nuclear initiators (neutron sources) would also be needed; nuclear initiators may be radioisotope based (α,n) or use small accelerators.

For the device to be militarily effective, planning for the military infrastructure to support and use the weapon must also proceed in parallel with weapons development. The military planning must include identification of the delivery system, tactical and strategic planning, development of command and control systems, and training for personnel involved in the nuclear armed force. This includes not only those responsible for delivery but also the ordnance experts who must maintain the weapons. This must be done early enough in the process that the weapons design will reflect the limitations imposed by the military requirements. A weapon that is too big for the available delivery platforms is of limited usefulness. In the absence of this planning, a nuclear weapon is little more than a propaganda device. However, it should also be pointed out that a militarily ineffective nuclear propaganda device can still be a highly effective political weapon.

C. Weaponization Pathway Analysis

Herein, "weaponization" is divided into

1) Acquisition and employment of the human resources and talents necessary for a nuclear development program;
2) Ordnance engineering activities/capabilities needed for development of a nuclear explosive capability; and
3) Military preparations, delivery system development, warhead integration and deployment, command/control communications, and intelligence related to or required for employment of a nuclear explosive.

Efforts by the international community to analyze information to detect weaponization should be focused on the detection of

1) Undeclared sites (conducting weaponization),
2) Activities inconsistent with other industrial or governmental efforts and with the potential to be applied to weaponizing nuclear material, and
3) Dual-use activities that singly may not be applicable to nuclear weapons but in combination may indicate weaponization activity.

The detection of weaponization activities depends on the ability to observe various signatures and indicators. A list of these is given in Table 8-I. It should be emphasized that in many cases these can be generated by legitimate activities. Their true significance will be apparent only when a combination of signatures or indicators is present.

TABLE 8-I. Signatures and Indicators of Weaponization

<u>Fissile Material Fabrication</u>

1) Facilities for converting fissile material to metal
2) Facilities for casting and machining fissile material

<u>High-Explosive Implosion Program</u>

3) Purchase of energetic high explosives (material better than pure TNT)
4) Equipment for melting and casting or pressing high explosive into shapes
5) Facilities for precise machining of high explosives
6) Waste and scrap from operations on high explosives
7) Purchase or development of detonators
8) Purchase of certain types of linear detonation cord (i.e., mild detonating fuse)

<u>Hydrodynamic Testing</u>

9) Bright streamers from test shots indicating the presence of uranium
10) Radiation monitoring equipment located around test shots
11) Permanently installed air monitors around firing points

<u>Gun Weapon Development Program</u>

12) Use of medium-speed framing cameras
13) Different noises and little visible flash as compared to a high-explosive detonation

<u>Criticality Testing</u>

14) Remotely operated experiments
15) Appropriate detectors to measure large neutron fluxes
16) Closed-circuit televisions for monitoring experiments
17) Possible history of criticality accidents

<u>Computational Physics Models</u>

18) Numerical hydrodynamics models with shock propagation
19) Equation of state properties for fissile material at extreme conditions
20) Time-dependent neutron transport models
21) Neutron cross sections
22) Explosive burn models
23) Good computing facilities with high security

TABLE 8-I (cont)

Nuclear Testing

24) Importing or developing computer codes for analyzing high-speed data
25) Instrumentation including plastic scintillators, photodiodes, photomultipliers, and high-bandwidth oscilloscopes with cameras
26) Drilling rigs, mining operations, for example, in new, remote locations
27) Large diameter pipe (about 1.2 m) for casings

Personnel and Publications

28) Movement of top scientists to undisclosed or inaccessible locations
29) Sudden decline or cessation in the number of published papers by top scientists
30) Extensive technological training or exchange programs with countries with advanced nuclear or other high-technology capabilities
31) Recall of trained scientists from other countries
32) Close association of top scientists with diversified backgrounds (e.g., hydrodynamicists with nuclear physicists)
33) Publication of papers on areas of interest in nuclear weapons (critical mass data, nuclear reactor "excursions," high-explosives testing)

Ordnance Engineering

34) Expansion of facilities or the number of personnel or both at or near existing ordnance plants
35) Purchase or development of high-explosive detonators, high-speed switching circuitry, advanced technology capacitors and related energy storage devices, for example, useful for arming, fusing, and firing nuclear weapons

Military Preparations for Use

36) Development of command and control systems appropriate for nuclear weapons
37) Characteristic training for personnel involved in nuclear weapon maintenance, delivery, and military employment
38) Development of delivery systems appropriate for nuclear weapon delivery (e.g., long-range missiles)

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[a] Based in part on Paternoster, 1992. See list of sources.

II. OBJECTIVES

Table 8-II contains a brief summary of the objectives of an enhanced safeguards program to address the weaponization proliferation pathway. Note that in contrast to other pathways, there is no legitimate form of nuclear weaponization for a non-nuclear weapon state subject to IAEA safeguards. Further, the detection of a possible weaponization program may be partially or totally masked by legitimate activities such as production of conventional munitions.

TABLE 8-II. Objectives of Enhanced Safeguards to Detect Weaponization

Objective 1	Detect activities at undeclared sites that are consistent with weaponization activities.
Objective 2	Detect activities at declared facilities that are a) Inconsistent with the facility's normal function and b) Consistent with weaponization activities.
Objective 3	Detect activities at declared facilities that are a) Consistent with the facility's normal function and b) Consistent with weaponization.
Objective 4	Detect research and development activities in potential proliferating countries that appear to lead to weaponization.
Objective 5	Demonstrate to the international community that weaponization is not occurring (sometimes referred to as transparency, e.g., in the context of the Chemical\Biological Weapons Convention.)

III. NEEDS

Table 8-III lists enhanced safeguards needs for the detection of weaponization. These needs can be divided into two groups:

1) Needs that relate to the detection of weaponization activity, e.g., detection of undeclared sites, and legitimate activities that may, in combination with other information, be indicators of weaponization. Such needs include an improved definition of weaponization signatures at declared and undeclared sites (1, 2), identification and tracking of personnel, technologies, industries, and materials of concern in potential proliferant countries (3, 4, and 5), and improved capabilities to detect undeclared sites involved in weaponization (5,7).

2) Needs 8, 9, 10, and 11 address the most effective way to detect weaponization without releasing information of value to proliferants. These needs include an assessment of what weaponization information should be released or releasable to the international community, i.e., IAEA, and the most efficient way of transferring this information.

TABLE 8-III. Possible Weaponization-Related Needs

Detection of Weaponization:	
Need 1	Study and list signatures (including environmental signatures) that could be used to detect activities characteristic of weaponization at undeclared sites.
Need 2	Study and list signatures (including environmental signatures) that could be used to detect activities characteristic of weaponization at declared sites.
Need 3	List dual use technologies, industries, and materials useful for weaponization and identify these in potential proliferant countries.
Need 4	Identify characteristic technical disciplines necessary for weaponization and relate these to personnel in potential proliferant countries.
Need 5	Recognize and construct means of tracking activities that are characteristic of weaponization and inconsistent with other activities.
Need 6	Enhance capabilities to detect undeclared weaponization sites.
Need 7	Develop equipment and methods to detect weaponization signatures.
Helping the International Community to Detect Weaponization:	
Need 8	Determine the best institutional approach to allow the detection of weaponization.
Need 9	Study and assess the nature of weaponization information that can be released to the IAEA.
Need 10	Provide the IAEA with appropriate information on weaponization and its detection.
Need 11	Develop ways to facilitate IAEA involvement in weaponization detection.

The specific safeguards needs are more fully described as follows.

Need 1: Study and list signatures (including environmental signatures) that could be used to detect activities characteristic of weaponization at undeclared sites.

Need 1 addresses the development of a list of observables that could indicate activities consistent with or characteristic of weaponization at a specific site. Although most of these signatures are understood individually, it is important to assemble them in a single list so that patterns and synergistic interactions in the technologies that might be applied to their detection can be more easily seen. Further, this will assist in the task of transferring this information to the inspectorate responsible for detecting weaponization.

Need 2: Study and list signatures (including environmental signatures) that could be used to detect activities characteristic of weaponization at declared sites.

Need 2 extends the listing of signatures to declared sites. Although it is unlikely that a potential proliferant would choose to use a declared site for weaponization-related activities, certain special resoures in a country may be limited to its declared sites, forcing their use. An example might be facilities to handle plutonium. These also may be the only places in a country to which an international inspectorate has ready access.

Need 3: List dual use technologies, industries, and materials useful for weaponization and identify these in potential proliferant countries

Need 3 is concerned with identifying and documenting dual-use technologies and industries that exist in potential proliferant countries and relating these industries to weaponization-related activities that may be concealed under their "umbrella." For example, technology for the production of depleted uranium penetrators may be applied to the fabrication of HEU components.

Need 4: Identify characteristic technical disciplines necessary for weaponization and relate these to personnel in potential proliferant countries.

Need 4 addresses the requirement that a proliferant country develop the human resources necessary to successfully carry out a nuclear weapon development program. This includes developing a list of disciplines that such a country would require and, possibly, sources of acquiring such expertise. Using available technical groups and organizations, for example, as sources of information, may be a part of fulfilling this need. It might also include tracking an individual's technical activities such as publications, research projects, and conferences attended.

Need 5: Recognize and construct means of tracking activities that are characteristic of weaponization and inconsistent with other activities.

Need 5 concerns the need to track activities that are uniquely characteristic of weaponization in potential proliferant countries or that appear to have no other legitimate industrial or governmental application than those associated with the development of a nuclear explosive capability. This might include the fabrication of large parts made of SNM or spherical explosive lenses.

Need 6: Enhance capabilities to detect undeclared weaponization sites.

Need 6 addresses the means of characterizing and then identifying undeclared sites where activities required as part of a weapon development program could be or are being conducted. This is possibly the most important need because most weaponization activities will be conducted at undeclared sites.

Need 7: Develop equipment and methods to detect weaponization signatures.

Need 7 is about developing ways to monitor signatures and indicators that might show that a potential proliferant country was engaged in weaponization. Possible observables have been listed in Table 8-I.

Need 8: Determine the best institutional approach to allow the detection of weaponization.

Need 8 is concerned with the problem of determining the best institutional arrangement for the detection of weaponization. Possibilities include the use of the IAEA, some other type of international body, or the use of national resources.

Need 9: Study and assess the nature of weaponization information that can be released to the IAEA.

Need 9 relates to the issue of providing the IAEA with information relating to weaponization which will allow the Agency to appropriately address the detection of weaponization programs, while at the same time ensuring that this same information, if inadvertently acquired by a potential proliferant country, would not provide them with useful information of how to successfully weaponize a nuclear explosive design. This need as well as 10 and 11 are dependent on a policy decision that would encourage IAEA participation in the detection of weaponization.

Need 10: Provide the IAEA with appropriate information on weaponization and its detection.

Need 10 addresses the means of most effectively and efficiently providing the IAEA with information on weaponization. This would include the development of appropriate textbooks and other instructional materials.

Need 11: Develop a way to facilitate IAEA involvement in weaponization detection.

Need 11 addresses the requirement to develop the most effective way of involving the IAEA in weaponization detection. The current IAEA inspection procedures are not designed to address the detection of weaponization. Among the possible ways of addressing weaponization are changes to the present inspection system, use of environmental monitoring data, and collection and use of information other than that obtained through normal safeguards channels (declarations and inspections).

IV. OPTIONS

Table 8-IV contains a list of possible options for improving the IAEA's ability to detect weaponization activities. These options are based on the needs identified above. Options are divided into five categories:

- Systems Studies;
- Instrumentation, Equipment, and Methods;
- Information Systems;
- Training; and
- Inspection Procedures.

The first category, Systems Studies, lists a series of options for studies that address the needs presented in Table 8-II and described above. They try to both improve the capability to detect weaponization and investigate the best way for the international community to deploy these improved capabilities. The Instrumentation, Equipment, and Methods category as well as the Information Systems category is concerned with the development of the tools necessary to carry out the desired policy. Finally, implementation is addressed in the Training and Inspection Procedures categories.

The specific safeguards options along with an indication of the need(s) they meet are described below:

Option 1: Study of the Possible Institutional Arrangements to Allow the International Community to Detect Weaponization

Option 1 (meets Need 8) examines the advantages and disadvantages of the many different ways that the international community could address the weaponization detection problem. Although the IAEA is a leading candidate for this role, other arrangements are possible and should be explored.

TABLE 8-IV. Possible Weaponization Detection Options

Systems Studies	
Option 1	Study of the possible institutional arrangements to allow the international community to detect weaponization
Option 2	Study of weaponization information releasable to the IAEA
Option 3	Study of the sources and possible safeguards of weaponization-sensitive materials and components worldwide
Option 4	Assessment of capabilities and their integration into the IAEA to allow detection of weaponization
Option 5	Applying lessons learned from Iraq with respect to dual-use equipment and material
Option 6	Lessons learned from the chemical weapons convention (CWC) and the biological weapons convention (BWC) for the IAEA
Option 7	Development of a declaration and monitoring system for ordnance facilities
Option 8	Study of the use of commercial satellite imagery to detect weaponization
Instrumentation, Equipment, and Methods	
Option 9	Development of improved methods for the detection of trace explosives and their residues
Option 10	Development of radiation-based methods for the detection of weapons-usable material in metallic form in closed containers
Option 11	Surveillance and design verification of formerly used weaponization facilities
Information Systems	
Option 12	Development of a database of the export of materials used in weaponization (e.g., high-purity bismuth, depleted uranium, lithium, and deuterium).
Option 13	Development of a database of ordnance facilities
Option 14	Develop a database of scientists, engineers, and technicians in disciplines related to weaponization
Training	
Option 15	Training and handbook on weaponization for IAEA inspectors
Option 16	Procedures for special inspections at weaponization facilities

Option 2: Study of Weaponization Information Releasable to the IAEA

Option 2 (meets Needs 1, 2, 9) addresses what ordnance engineering-related weaponization information could be released to the IAEA. Obviously, it is important that no sensitive information be given to potential proliferant countries that might benefit their nuclear weapons program. Because of the international nature of the IAEA, great care must be taken in deciding what information to release. One possible solution is multiple levels of release to accommodate security concerns.

Option 3: Study of the Sources and Possible Safeguards of Weaponization-Sensitive Materials and Components Worldwide

Option 3 (meets Need 3) is a study to determine possible sources of some of the special materials that are important to the development of some nuclear weapon designs and that may be used as part of a weaponization program (e.g., depleted uranium, lithium, high-purity bismuth, deuterium, and tritium). This study would also address the sources of specialized electrical and mechanical weapon components. The final product in addition to the source information would be recommendations on possible schemes to regulate the flow of these commodities.

Option 4: Assessment of Capabilities and their Integration into the IAEA to Allow Detection of Weaponization

Option 4 (meets Need 11) is a study that would review the present structure of IAEA safeguards and propose more effective ways to integrate activities related to the detection of weaponization into this existing structure. These could include such measures as expanded routine inspections, *ad hoc* inspections, and environmental sampling.

Option 5: Applying Lessons Learned from Iraq with Respect to Dual-Use Equipment and Material

Option 5 (meets Need 3) would examine experience gained in Iraq to determine the sources and application of dual-use items in the Iraqi nuclear weapon program and how such items can be tracked by or for the IAEA. This is an area of some concern because of the potential economic damage done by overly aggressive export controls. However, the Iraq experience is quite clear on the importance of controlling the movement of these items.

Option 6: Lessons Learned from the CWC and the BWC for the IAEA

Option 6 (meets Needs 8 and 11) would collate information on inspection procedures developed under the CWC and the BWC and apply them to the weaponization detection problem that could be faced by the IAEA. Both the CWC and the BWC address highly complex arms control problems. Experience gained from them may be of benefit particularly in the design of some of the extended safeguards options now being considered for the IAEA.

Option 7: Development of a Declaration and Monitoring System for Ordnance Facilities

Option 7 (meets Needs 3, 4, and 6) would develop a declaration and monitoring system for ordnance facilities. Because the development of conventional armaments can serve as a cover for nuclear weapons development, various types of ordnance facilities might serve as convenient locations for weaponization activities. The contemplated reporting system could be similar to the annual reports under the BWC that describe a facility's location and functions.

Option 8: Study of the Use of Commercial Satellite Imagery to Detect Weaponization

Option 8 (meets Needs 1 and 6) would examine the possibility of the IAEA using commercially available satellite imagery to detect weaponization. Detection of weaponization facilities is quite difficult because they need not be large and would generally be sited in remote areas. Satellite observation is of interest because of its ability to cover wide areas. However, for financial reasons a dedicated system for IAEA use is unlikely. Commercial satellite imagery may provide an affordable alternative.

Option 9: Development of Improved Methods for the Detection of Trace Explosives and their Residues

Option 9 (meets Needs 1, 2, 4, 6, and 7) would address capabilities and improve existing means to detect explosive residues and byproducts using environmental sampling. As with many of the signatures associated with weaponization, explosive residues are not an unambiguous sign of weaponization. However, along with traces of uranium, it may be the only way to detect a covert site. The signature can also be made somewhat less ambiguous if it can be determined that high-energy explosives are in use.

Option 10: Development of Radiation-Based Methods for the Detection of Weapons-Usable Material in Metallic Form in Closed Containers

Option 10 (meets Needs 2 and 7) would address the development of a radiation-based technique to rapidly screen material in storage to determine if large quantities of weapons-usable material in metallic form are present. Because of its high density, metal is the most desirable form for the fissile material in a weapon. Although metal is used in some reactors, it is not the usual form. Therefore, a rapid means of screening containers in storage may be of use.

Option 11: Surveillance and Design Verification of Formerly Used Weaponization Facilities

Option 11 (meets Needs 2 and 7) is concerned with developing a capability to ensure that shutdown weaponization facilities remain decommissioned. As in Iraq, it may be necessary to monitor closed weaponization sites for some time. Because of the high costs associated with on-site inspection, it is important to find alternative ways of achieving the same results.

Option 12: Development of a Database for Exported Materials Used in Weaponization (e.g., high-purity bismuth, depleted uranium, lithium, and deuterium)

Option 12 (meets Needs 1, 2, 3, and 5) would help the IAEA track weaponization-sensitive materials. At present the Agency has little or no knowledge of the movement of these materials. In combination with other signatures and indicators, this information may provide a composite picture of a potential proliferant's weaponization program.

Option 13: Development of a Database of Ordnance Facilities

Option 13 (meets Needs 2 and 6) would help the IAEA track ordnance facilities worldwide. This option combined with the declaration system in Option 7 would both indicate a logical place to look for weaponization and possibly dissuade a potential proliferant from the use of such facilities for nuclear weapons development.

Option 14: Develop a Database of Scientists, Engineers, and Technicians in Disciplines Related to Weaponization

Option 14 (meets Needs 4, 6, and 7) is concerned with the development of a database to trace the human assets of a potential proliferant country's weaponization program. This type of database could provide warning of the initiation of a weaponization program as well as have some capability to judge its progress.

Option 15: Training and Handbook on Weaponization for IAEA Inspectors

Option 15 (meets Needs 10 and 11) would develop the necessary training materials to allow IAEA inspectors to look for weaponization. This search could take place either as part of routine inspections or could be based on other types of inspection. Either type of inspection could use information developed outside of normal safeguards channels.

Option 16: Procedures for Special Inspections at Weaponization Facilities

Option 16 (meets Needs 10 and 11) would develop the necessary procedures to inspect weaponization sites during special inspections. Because of the limited number of signatures associated with weaponization and their general ambiguity, this type of inspection is very important in proving the existence of weaponization programs. Therefore, it is important that the IAEA be provided with carefully chosen procedures for efficiently carrying them out.

REFERENCES ON WEAPONIZATION

Department of Safeguards, "Safeguards Research and Development Programme," International Atomic Energy Agency, Vienna, Austria (December 12, 1991, Updated June 26, 1992).

J. E. Dougherty, "A Summary of Indicators of Nth Country Weapon Development Programs," Los Alamos Scientific Laboratory report LA-6904-MS (January 1978).

S. Glasstone and P. J. Dolan, "The Effects of Nuclear Weapons," US Department of Defense and the Energy Research and Development Administration, Third Edition (1977).

F. G. Gosling, "The Manhattan Project: Science in the Second World War," US Department of Energy report DOE/MA-0417P/Reprint (June 1992).

R. K. Paternoster, "Nuclear Weapon Proliferation Indicators and Observables," Los Alamos National Laboratory report LA-12430-MS (December 1992).

R. Serber, *The Los Alamos Primer* (University of California Press, Berkeley, 1992).

CHAPTER 9

OPTIONS DERIVED FROM MULTIPLE PATHWAYS

Figure 9-1 graphically displays the approximate distribution of safeguards options identified in the foregoing chapters. As explained in Chapter 2, some of the options developed from each pathway duplicate those in other pathways. It is of particular importance to identify these options because they make more efficient use of available support funds. Therefore, the options from each of the pathways discussed above have been reviewed, and those options that are essentially duplicates have been tabulated. These options may be found in Table 9-I. As in previous sections, these are technical options. The desirability of any of them is dependent on a review of the policy implications.

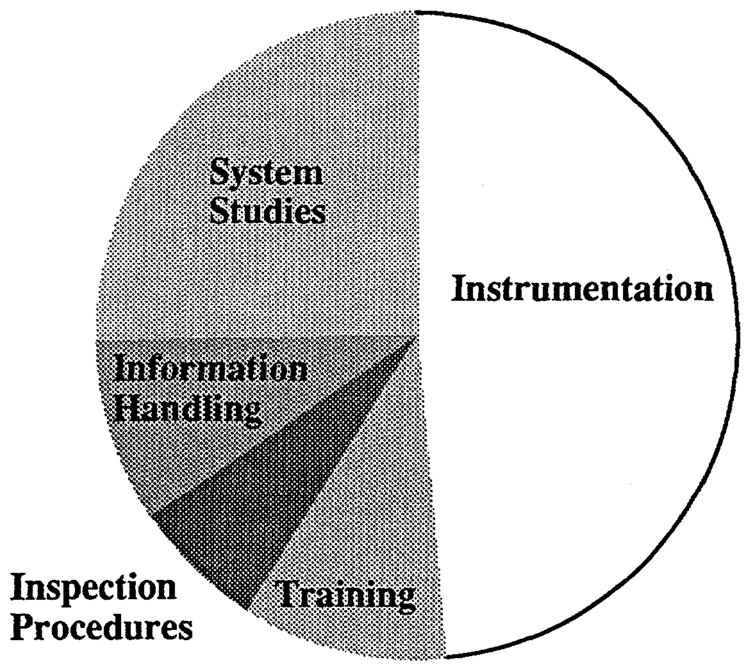

Fig. 9-1. Distribution of classes of safeguards options identified in this study.

TABLE 9-I. Options Appearing in Multiple Pathways

Option 1	Study the use of commercial satellites for detection of undeclared sites
Option 2	Develop a data system for use by inspectors in the field
Option 3	Expand inspector training to include information on potential proliferation signatures and indicators
Option 4	Develop uranium and plutonium analysis systems that can be used in the field
Option 5	Develop procedures and appropriate training for environmental monitoring
Option 6	Develop proliferation-related information management systems
Option 7	Improve the capability to verify design information at complex facilities
Option 8	Improve tags and seals for safeguards purposes
Option 9	Study ways to authenticate information from facility control systems
Option 10	Develop unattended monitoring equipment for use in bulk processing facilities
Option 11	Develop procedures for use during non-routine inspections

Option 1: Study the Use of Commercial Satellites to Detect Undeclared Sites

Obtaining access to a country to search for undeclared sites may prove difficult for any international inspectorate. Currently, national technical means such as reconnaissance satellites provide an observational capability for some states. However, an international inspectorate may not be able to obtain this information because of security restrictions. Further, developing their own capability would be financially prohibitive. Satellite imagery is currently available commercially from Landsat and SPOT, and additional images may soon become available from Russian and US reconnaissance satellites. This option, shown schematically in Fig. 9-2, would study the potential for an international inspectorate to use these assets to detect undeclared nuclear facilities or weaponization activities.

Option 2: Develop a Data System for Use by Inspectors in the Field

To make the most of any type of inspection, it is important for the inspectors to have relevant information readily available. This option would develop portable data systems tailored to the needs of inspectors engaged in nonproliferation-related inspections. Features might include access to information stored in the system as well as access to information at remote sites.

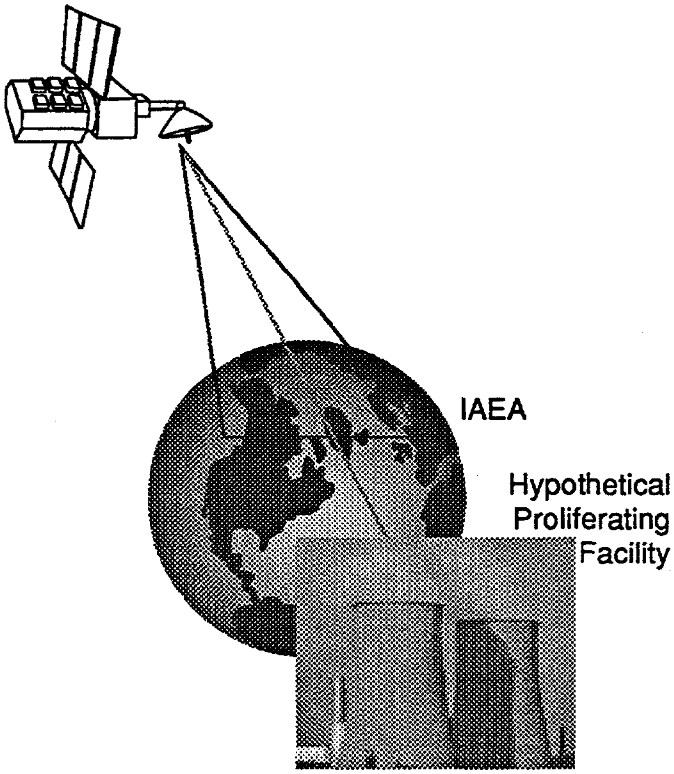

Fig. 9-2. Use of commercial satellites to detect undeclared sites.

Option 3: Expand Inspector Training to Include Information on Potential Proliferation Signatures and Indicators

Current practice in IAEA inspections is to limit the information-gathering capability of inspectors to certain prearranged areas and times. In the future these restrictions could be modified. In this event inspectors may have the chance to make other types of observations. As in Fig. 9-3, this option addresses the training that would be necessary to allow inspectors to recognize possible evidence of proliferation-related activities.

Option 4: Develop Uranium and Plutonium Analysis Systems That Can Be Used in the Field

In a number of proliferation pathways, the presence and enrichment of uranium or plutonium may provide valuable information as to the proliferation activities of a facility under inspection. As in any inspection it is desirable to obtain the results of analyses while the inspection team is in the field. This allows an inspector to obtain additional information that may be of importance in resolving any anomalies. Further, on-site analysis may be less intrusive if it precluded the removal of samples for off-site analyses that could reveal sensitive information. This option, therefore, is concerned with the development of the necessary instrumentation for the on-site analysis of uranium or plutonium.

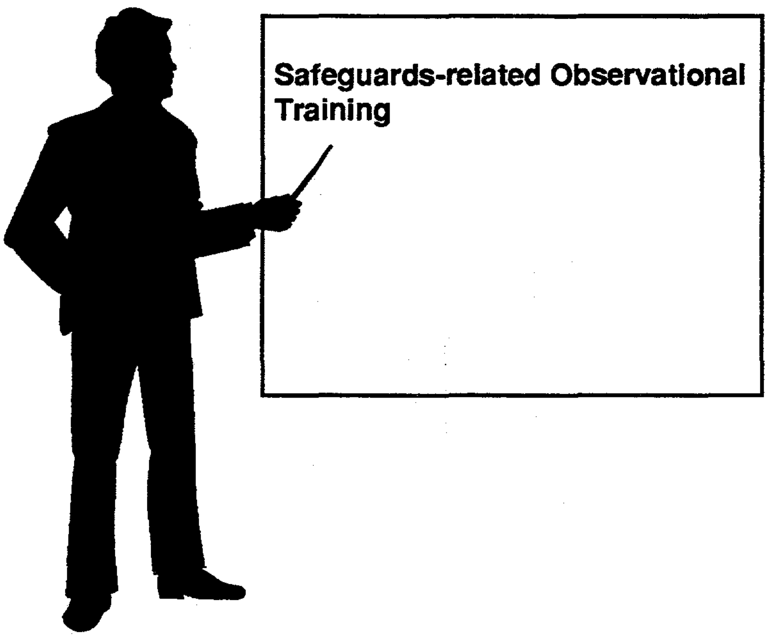

Fig. 9-3. Expand inspection training.

Option 5: Develop Procedures and Appropriate Training for Environmental Monitoring

Nuclear activities, including those related to proliferation, often introduce trace quantities of material into the environment that are indicative of their nature. Often these materials, as Fig. 9-4 suggests, will persist long enough in the environment that removal of samples for analysis is feasible. This option involves the development of appropriate sampling techniques for use by international inspectors. In addition, it would develop a training course for the inspectors.

Option 6: Develop Proliferation-Related Information Management Systems

As discussed in this report, many possible indicators of proliferation intent may be available from open sources. In addition, traditional and enhanced safeguards inspections provide even more information. This could result in an information "glut." Modern data systems can readily be used not only to manage and display information but also to automate the analysis process. Figure 9-5 illustrates one example to automate analysis of proliferation-related information from a variety of sources. This option would develop appropriate systems for international inspectors.

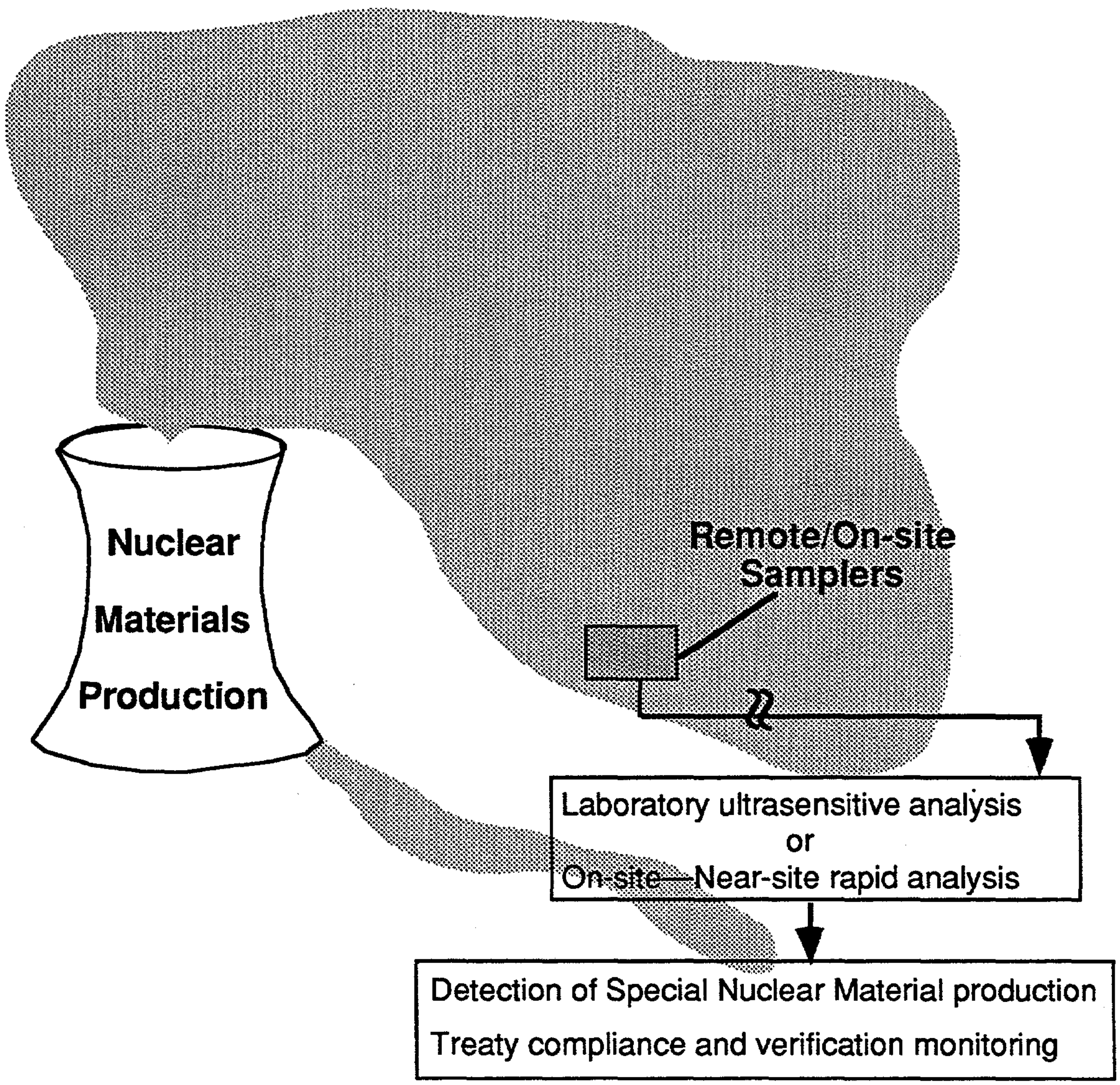

Fig. 9-4. Environmental or remote unattended monitoring.

Option 7: Improve the Capability to Verify Design Information at Complex Facilities

A necessity in any facility is for the inspector to understand how the facility functions. An important part of this is the ability to determine that the facility is built according to the design in a declaration such as a Design Information Questionnaire. However, in a complex facility this may be quite difficult. The problem is made worse by high radiation or other hazards that are present after a facility begins operation. This option addresses ways to improve an inspectorate's ability to verify a design.

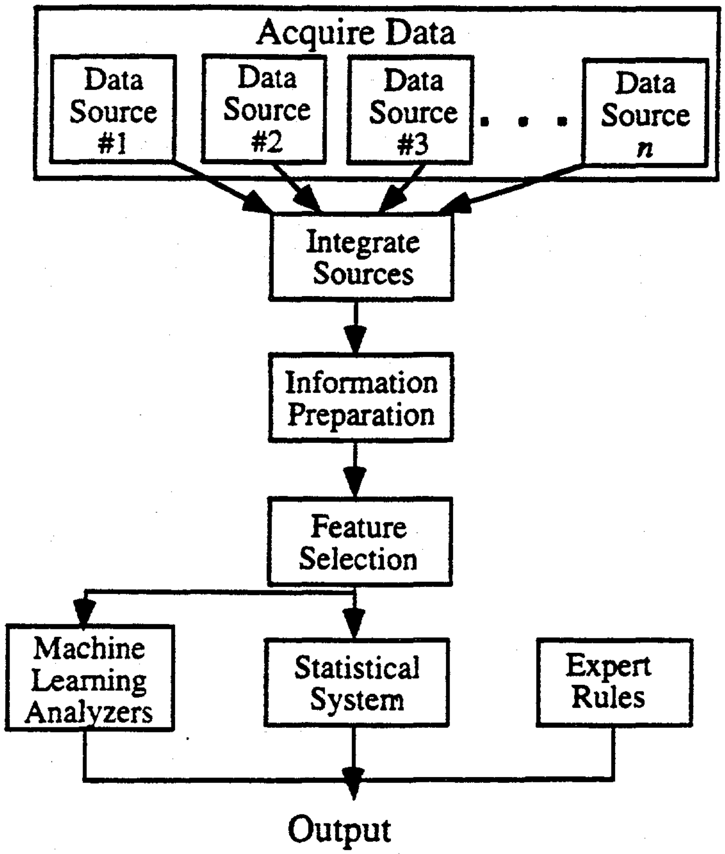

Fig. 9-5. Proliferation-related information management systems.

Option 8: Improve Tags and Seals for Safeguards Purposes

Safeguards strategies involve the use of tamper-indicating seals and tags. The adequacy and cost of various types of seals and tags is always a topic of some concern. A continued effort in this area appears to be important to several different pathways.

Option 9: Study Ways to Authenticate Information from Facility Control Systems

Modern nuclear facilities rely heavily on automated control and information systems. Much of the data that is collected by these systems could be of value to international safeguards. However, the reliability of this information depends on the ability to assure that it is accurate when it is taken, that it is transmitted accurately to the point of display or storage, and that it maintains its integrity while it is in storage. This option concerns a study of improved ways of providing the necessary authentication.

Option 10: Develop Unattended Monitoring Equipment for Use in Bulk-Processing Facilities

Inspector time is both costly and in short supply, yet current safeguard procedures for bulk-processing facilities rely on heavy commitments of inspector time. One solution is to employ continuous monitoring instrumentation that could be remotely monitored. These types of systems include the instrumentation itself, secure communication systems, and a means of authenticating the data. Because of the potential for large savings of inspector time, this becomes a very attractive option.

Option 11: Develop Procedures for Use During Non-Routine Inspections

INFCIRC/153 provides for special inspections, when routine inspections are inadequate, to assure that no inappropriate activities are taking place. In addition, a number of other types of non-routine inspections have been carried out in the recent past. Most of these inspections required short lead times to be effective. This option is concerned with developing particular procedures for various situations. These preplanned procedures would increase the efficiency of any non-routine inspections required.

CHAPTER 10

PROJECT EVALUATION METHODOLOGY

This document is intended to aid in developing project proposals that are relevant to current and enhanced safeguards needs and objectives. Evaluating proposals is an integral part of this process. Ideally, evaluation would be performed both by the laboratory originating the proposal and by the intended project manager.

The project evaluation methodology developed during the study involves a series of criteria that were based on the options development methodology. The project evaluation methodology was developed to meet several goals. These include an appropriate format for the submission of project proposals, a prioritization scheme that reflects the priorities in enhanced safeguards, and a prioritization scheme that further maximizes the likelihood of a successful project. A successful project is one in which the product is operational and useful to the end user.

Criteria described in Appendix D along with the instructions for the reviewer provide the key to the evaluation methodology. These instructions are reflected in the project description form and instructions for the principal investigators in Appendix D. The five criteria are listed in Table 10-I. The scoring scheme is also described in this appendix.

TABLE 10-I. Safeguards Options Project Evaluation Criteria

- Safeguards Needs
- Success of the Project
- Enhancement of Safeguards
- Research and Development Factor
- Comments

The first of the criteria shown in Table 10-I captures the requirement that the project addresses real safeguards needs. These needs are to be drawn from those developed during the Safeguards Options Study for each of the pathways as well as from the literature on proliferation.

The second criterion is based on a technical judgment by the reviewer of the chances that the project will result in the delivery of a successful product to the customer. The factors that need to be considered here include not only the technical ability to produce something but also the ability to produce something that is useful to the end user.

The third criterion concerns whether the project will improve the overall safeguards efficacy and efficiency. This includes an evaluation of the project in light of competing technologies.

The research and development factor is not used to evaluate the merit of the project, but as a way of determining the proper program element within DOE to perform the work. In general, the ISD program will support projects aimed at packaging and implementing products for use in international safeguards. Projects requiring substantial research are more appropriately funded elsewhere.

The final criterion is a way to capture any special factors that might have a bearing on a project's priority. These special factors may have a positive or negative influence.

APPENDIX A

AN ANNOTATED BIBLIOGRAPHY OF SOURCES ON PROLIFERATION PATHWAYS AND THEIR SIGNATURES

Published Reports:

"Environmental Survey of the Nuclear Fuel Cycle," US Atomic Energy Commission (November 1972). This report reviews the environmental effluents and impacts expected from the civilian US nuclear fuel cycle. The report goes into some detail on the quantities and types of effluents that are produced at the most common types of US facilities. Facilities for plutonium recycling were not considered. For the parts of the fuel cycle covered, this is a good source for average effluents from US-type facilities.

"Environmental Survey of Transportation of Radioactive Materials to and From Nuclear Power Plants," US Atomic Energy Commission, WASH-1238 (December 1972). A survey of transportation-related environmental impacts. The principal application to nonproliferation may be in understanding releases during accident situations. However, it only reflects US practices.

"Environmental Survey of the Uranium Fuel Cycle," US Atomic Energy Commission, WASH-1248 (April 1974). An updated version of USAEC 1972 that is restricted to the uranium portion of the fuel cycle. Most of the update responds to comments made on the original report. Like its predecessor it is a good source of average effluent data for the US facilities covered.

"The Generic Environmental Statement of the Use of Recycle Plutonium in Mixed Oxide Fuel in LWRs, Volume 2," US Atomic Energy Commission, NUREG/002 (August 1976). A review of the environmental impacts associated with the production and use of mixed oxide fuel. The report describes the implementation of a plutonium recycling system as well as the various types of impacts and their mitigation. This is a good source of average effluent data for US facilities.

"Environmental Survey of the Reprocessing and Waste Management Portions of the LWR Fuel Cycle," W. P. Bishop and F. J. Miraglia, Eds., Office of Nuclear Material Safety and Safeguards, U. S. Nuclear Regulatory Commission (October 1976). This is a generic study of environmental impacts of the reprocessing and waste disposal portions of the civilian nuclear fuel cycle. Some more specific data are provided for model facilities as necessary. Estimates are given of both the types and quantities of effluents expected.

"Nuclear Proliferation and Safeguards," Congress of the United States, Office of Technology Assessment, Praeger, New York (1977). A broad overview of issues involved in nuclear nonproliferation. It addresses the policy aspects of the problem rather than the technical aspects. It includes material on the US domestic nuclear industry as well as foreign countries. It has become somewhat dated, but might serve as an introduction for someone new to the field.

"The Effects of Nuclear Weapons," Samuel Glasstone and Phillip J. Dolan, Third Edition, US DOD and ERDA (1977). This is the most recent version of the classic work. In addition to the weapons effects, there is a good unclassified description of weapons and how they work.

"A Summary of Indicators of Nth Country Weapons Development," J. E. Dougherty, Los Alamos Scientific Laboratory, LA-6904-MS, (January 1978). This report summarizes indicators and observables of a nuclear weapons program. The indicators are presented with little or no discussion. See Paternoster, 1992 for an updated and expanded version of this report. At the time it was written this was considered a seminal work.

"Nuclear Proliferation and Civilian Nuclear Power, Report of the Nonproliferation Alternative Systems Assessment Program," US Department of Energy (June 1980). A high-level review of proliferation concerns related to the growth of the use of nuclear energy for power production. It summarizes some of the proliferation consequences of various choices in the development of civilian nuclear power. This is a multivolume work covering the entire civilian fuel cycle.

"Uranium Enrichment Export Control Guide: Gaseous Diffusion," Martin Marietta Energy Systems, Inc., K/ITP-111 Second Printing (January 1990). Describes general principles as well as special design features in great detail. It also has sections on the "Trigger List" and the applications of export controls in this area. There is no information on effluents. It is partly teaching material for the DOE nonproliferation courses.

"A Practical Guide to PASE," A. R. Garlick, P. M. Shaw and J. Hill, United Kingdom Atomic Energy Authority, IAEA 16 (March 1990). Describes the concepts and application of PASE (Probabilistic Assessment of Safeguards Effectiveness). This is a system for understanding diversion paths for nuclear material in facilities under IAEA safeguards. The report also describes the computer codes developed to assist the process. PASE is illustrative of a number of safeguards systems evaluation methods.

"PASE Assessment of a Spent Fuel Reprocessing Plant," T. F. Moriarty and R. F. Cameron, Australian Nuclear Science and Technology Organization, ANSTOC/C-208 (March 1991). Describes the application of the PASE methodology (See United Kingdom Atomic Energy Authority 1990) to a model reprocessing plant based on the Tokai Reprocessing Plant in Japan. The purpose of the study was to examine the effectiveness of safeguards for such a facility and identify ways to improve the safeguards system. The report also describes proposed changes in the PASE methodology that would be necessary to correct problems that arose during the study.

"Uranium Enrichment Export Control Guide: Gas Centrifuge," Martin Marietta Energy Systems, Inc., K/ITP-324 (May 1992). Describes general principles as well as special design features. There are sections on each of the components of a centrifuge system. The report also describes the development of the "Trigger List" and the application of export controls. There is no information on effluents. This is part of the course material for the DOE nonproliferation courses.

"Nuclear Weapon Proliferation Indicators and Observables:, Richard B. Paternoster, Los Alamos National Laboratory, LA-12430-MS (December, 1992). Describes indicators and observables that might be present from different parts of a nuclear weapon development program. This is a revision and amplification of Dougherty, 1978. The report covers both the SNM production and weaponization parts of proliferation. The SNM production sections list specific effluents, but not quantities. The report does provide some information on the source of some of the signatures. This is the best of the indicator sources in the open literature.

"Global Proliferation-Dynamics, Acquisition Strategies, and Responses," Volume 1, Overview, L. Dunn, et al., Center for Verification Research (December 1992). An overview of problems associated with the proliferation of nuclear, chemical, and biological weapons as well as missiles. This is a study done for the Defense Nuclear Agency. This is a very high-level discussion of proliferation.

"The Los Alamos Primer," Robert Serber, University of California Press, Berkeley (1992). This is an extensively annotated version of notes on a series of orientation talks given to new scientists arriving at Los Alamos during the Manhattan Project. It is an unclassified description of the physical basis of weaponization. For this edition Serber, who gave the original talks, has added extensive annotations to further explain the material in the notes taken by Ed Condon. The historian Richard Rhodes provided an introduction and edited the book.

"Nuclear Energy and Nonproliferation Workshop, Part 5: Isotope Enrichment," D. F. Starr, Martin Marietta Energy Systems, Inc., K/NSP-121/Part 5 (March 1993). Viewgraphs describe isotope enrichment technology for uranium, deuterium, lithium, and its proliferation significance. Information is provided on both foreign and domestic facilities. There is no information on emissions. This is part of the course material for the DOE nonproliferation courses.

"Nuclear Nonproliferation Workshop, Part 7: Nuclear Fuel Reprocessing," H. J. Clark, Westinghouse Savannah River Company, K/NSP-12/Part 7 (March 1993). Viewgraphs describe nuclear reprocessing to obtain plutonium and tritium. Also lists key questions to ask in evaluating a facility. Critical equipment is also listed. There is a description of effluents, but no quantitative data. Current and planned foreign reprocessing plants are also described. There is also a description of a "simple, quick reprocessing plant." This is part of the course material for the DOE nonproliferation courses.

"Nuclear Nonproliferation Workshop, Part 18: International Safeguards for Uranium Enrichment Plants," J. M. Whitaker, Martin Marietta Energy Systems, Inc., K/NSP-121/Part 18 (March 1993). Viewgraphs describe international enrichment plants, diversion paths, and current international safeguards for enrichment plants. There is a major section on the Hexapartite Safeguards Project. This is part of the course material for the DOE nonproliferation courses.

"Consultants Group Meeting on Environmental Monitoring and Special Analysis Methods for Safeguards," International Atomic Energy Agency (30 March - 2 April 1993). A very complete review of emissions from the different portions of the fuel cycle with an emphasis on those that could be detected through environmental sampling. The report contains information on the effluents, their amounts, and how much they may be concentrated in the environment. It also discusses analytical techniques, particularly in the context of what is currently available to the IAEA. It also makes recommendations on how sampling and analysis should fit into IAEA's mission and operations.

APPENDIX B

URANIUM

Tables

TABLE B-1. EXPLORATION

SIGNATURE	RELEASE FORM (OR LOCATION)	SIGNATURE/ PRODUCT	PRODUCT/ TIME	RELEASE RATE	DUTY CYCLE	CONCENTRATION AT RELEASE POINT	REF.	FOOT-NOTE
dust	drill site	9.3 - 209 kg/ borehole[1]	11.5 m/hr (drilling rate)	0.27 kg/min	pulsed		1 (Table 3.63)	1, 2, 3 2,3
CO	drill rig	20.2 kg/hole	11.5 m/hr (drilling rate)	1.5 kg/hr	continuous		1 (Table 3.65)	4
hydrocarbons	drill	7.4 kg/hole	11.5 m/hr (drilling rate)	0.55 kg/hr	continuous		1 (Table 3.65)	4
NO_x	drill rig	93 kg/hole	11.5 m/hr (drilling rate)	6.9 kg/hr	continuous		1 (Table 3.65)	4
aldehydes	drill rig	1.39 kg/hole	11.5 m/hr (drilling rate)	0.10 kg/hr	continuous		1 (Table 3.65)	4
SO_x	drill rig	6.2 kg/hole	11.5 m/hr (drilling rate)	0.46 kg/hr	continuous		1 (Table 3.65)	4
particulate	drill	6.6 kg/hole	11.5 m/hr (drilling rate)	0.49 kg/hr	continuous		1 (Table 3.65)	4
drill sites							1, 2	5

[1] 209 kg for dry drilling with air; 9.3 kg for mud, mist, or foam drilling.

2The ratio by weight of the chips, sand, and dust produced by drilling is approximately 60:37:3, respectively.

[3] Cuttings around the drill hole and/or in the drilling mud pit will contain uranium-bearing mineral if an ore zone has been penetrated and hence will exhibit higher than background radioactivity. Radon-222 and radon daughters should also be detectable at the mouth of the borehole, providing it is not plugged or capped.

[4] Diesel power source.

[5] Exploratory drilling is done on a grid with holes spaced 60 m to 1.6+ km. Development drill holes are spaced at 8 m to 100 m. The drill sites are leveled areas approximately 30 m × 45 m and are connected by a network of roads. There may or may not be a drilling mud pit (approximately 1.5 m × 3 m) at the site. Hole diameters of ~7.4 cm are drilled to depths of ~ 1300 m; whereas holes with diameters of ~11.4+ cm are drilled to depths in excess of 1300 m.

TABLE B-II. URANIUM UNDERGROUND MINING

SIGNATURE	RELEASE FORM (OR LOCATION)	SIGNATURE/ PRODUCT	PRODUCT/ TIME	RELEASE RATE	DUTY CYCLE	CONCENTRATION AT RELEASE POINT	REF.	FOOT-NOTE
^{222}Rn	gas	26.7 Ci/t	114-2630 t/d	3.4-70.2 Ci/dx10^3	5 d/wk	309-942 pCi/l_{air} avg.	3	6
SO_x	gas	3.3 g/t	1500 t/d	5.0 kg/d	5 d/wk		2	1, 7
CO	gas	27.9 g/t	1500 t/d	41.9 kg/d	5 d/wk		2	1, 2
NO_x	gas	45.4 g/t	1500 t/d	68.1 kg/d	5 d/wk		2	1, 2
hydrocarbons	gas	4.6 g/t	1500 t/d	6.9 kg/d	5 d/wk		2	1, 2
particulate	exhaust	1.6 g/t	1500 t/d	2.4 kg/d	5 d/wk		2	1, 2
SO_4	effluent			8.4 l/d x10^6	continuous	13 mg/l	2	3
Cl	effluent			5.1-14.3 l/d x10^6	continuous	1.2-51 mg/l	2	3
Mo	effluent			5.1-14.3 l/dx10^6	continuous	0.2-5.0 mg/l	2	3
Na	effluent			5.1-14.3 l/dx10^6	continuous	95-200 mg/l	2	3
NH_3	effluent			5.1-14.3 l/dx10^6	continuous	0.05-19 mg/l	2	3
$NO_2 + NO_3$	effluent			5.1-14.3 l/dx10^6	continuous	0.53-1.14 mg/l	2	3
Se	effluent			5.1-14.3 l/dx10^6	continuous	0.01-0.07 mg/l	2	3
V	effluent			5.1-14.3 l/dx10^6	continuous	0.5-0.9 mg/l	2	3
Mn	effluent			5.1-14.3 l/dx10^6	continuous	0.05-0.8 mg/l	2	3
Total U	effluent			5.1-14.3 l/dx10^6	continuous	0.88-19 mg/l	2	8
^{226}Ra	effluent				continuous	200-3200 mg/l	4	
U_{nat}	ore	0.4-8 kg U_{nat}/t	114-2630 t/d	46-21x10^3 kg/d U_{nat}	5 d/wk	0.5-9.4 kg U_3O_8/t	3	1

[6] A unit of production is a ton (t) of ore mined. A work day = 2 shifts (8 hr each). 1 t = 0.90 MT. Ore cut-off grade (wt.% U_3O_8 in ore) is based on US underground uranium mining industry practice.

[7] Emission from earth hauling equipment.

[8] All effluent (mine discharge water) values other than ^{226}Ra are taken from Table 6 of Ref. 2. Values are representative of US underground uranium mines. Actual composition of mine discharge water is dictated by the composition of the aquifer and the rock formations through which the water flows.

TABLE B-III. URANIUM SURFACE MINING

SIGNATURE	RELEASE FORM (OR LOCATION)	SIGNATURE/ PRODUCT	PRODUCT/ TIME	RELEASE RATE	DUTY CYCLE	CONCENTRATION AT RELEASE POINT	REF.	NOTE
U_3O_8	ore	1.1 kg/MT	1545 MT/d	1.7 MT/d	7 d/wk	285 pCi/g (632 dpm/g)	1	9
U_3O_8	sub-ore	0.15 kg/MT	1545 MT/d	23 kg/d	7 d/wk	43 pCi/g (95 dpm/g)	1	
^{238}U	dust	4 kg/MT	1545 MT/d	6 MT/d	continuous	5-76 pCi/g	1	
^{230}Th	dust	4 kg/MT	1545 MT/d	6 MT/d	continuous	2-80 pCi/g	1	
^{226}Ra	dust	4 kg/MT	1545 MT/d	6 MT/d	continuous	3-70 pCi/g	1	
$^{238}U/^{232}Th$	dust	4 kg/MT	1545 MT/d	6 MT/d	continuous	4-63 pCi/g	1	
U_{total}	water			1-5 m^3/min	continuous	0.2-1.2 mg/l	1	2
^{226}Ra	water			1-5 m^3/min	continuous	0.7-7.5 mg/l	1	10
SO_x	gas	0.03 kg/MT	1350 MT/d	35-39 kg/d	7 d/wk		1	11
CO	gas	0.2 kg/MT	1350 MT/d	294-327 kg/d	7 d/wk		1	3
NO_x	gas	0.4 kg/MT	1350 MT/d	485-538 kg/d	7 d/wk		1	3

9 Mine operates 330 d/yr on day shift. A unit of production is a metric ton (MT) of ore mined. Ore cut-off grade (wt.% U_3O_8 in ore) is based on US uranium surface mining industry practice. Concentration values are based on US ore reserves, 97% of which are in sedimentary formations, primarily sandstones. These reserves are not representative of uranium ore reserves throughout the world.

10 Values for water are representative for US uranium surface mine water discharge. Actual composition of mine discharge water is dictated by the composition of the aquifer and the rock formations through which the water flows.

11 Emission from heavy equipment.

TABLE B-IV. URANIUM MILLING: ALKALINE LEACH

SIGNATURE	RELEASE FORM (OR LOCATION)	SIGNATURE/ PRODUCT	PRODUCT/ TIME	RELEASE RATE	DUTY CYCLE	CONCENTRATION AT RELEASE POINT	REF.	NOTE
U_3O_8	tail effluent	0.12 %	1814 MT/d	1.05 m^3/MT	continuous	6.8 ppm	2	12,13
Mn	"		"	"	"	0.01 ppm	2	2
Cu	"		"	"	"	0.01 ppm	2	2
Fe	"		"	"	"	1.0 ppm	2	2
Zn	"		"	"	"	0.6 ppm	2	2
SO_4	"		"	"	"	7500 ppm	2	2
CO_3	"		"	"	"	4000 ppm	2	2
HCO_3	"		"	"	"	1100 ppm	2	2
Th	"		"	"	"	2.0 ppm	2	2
Na	"		"	"	"	7100 ppm	2	2
U_3O_8	"	0.12 %	"	"	"	0.017 %	2	14
Mn	"		"	"	"	0.01 %	2	3
Cu	"		"	"	"	0.0028 %	2	3
Fe	"		"	"	"	1.36 %	2	3
Th	"		"	"	"	0.0005 %	2	3

12 A unit of production is a metric ton (MT) of ore processed.
13 Based on solution analysis. The pH of the tailings effluent is normally 9.5.
14 Solids analysis.

REFERENCES FOR TABLES IN APPENDIX B

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APPENDIX C

THORIUM

MINERAL RESOURCES

More than half of the world's identified resources of thorium are in beach placers, principally in India.[1] However, as of 1984 half of the world production of monazite was in Australia.[2] Table C-I[3] lists the principal thorium-containing minerals together with their nominal composition and some of the areas of the world where they are found.

TABLE C-I. Principal Thorium-Containing Minerals

Mineral	Nominal Composition	Examples of Where Found
Monazite	$(La,Ce,Th)PO_4$	Brazil, India, Sri Lanka Australia, South Africa, USA
Brockite	$(Ca,Ce,Th)[(PO_4) \cdot (CO_3)] \cdot H_2O$	USA
Thorianite	ThO_2	Sri Lanka, Canada
Uranothorianite	$(U,Th)O_2$	Malagasay Republic
Thorogummite	$ThO_2 \cdot UO_3$	Brazil
Thorite	$ThSiO_4$	Idaho and Montana, USA
Aueralite	$ThSiO_4$ YPO_4	Idaho and Montana, USA
Uranothorite	$(U,Th)SiO_4$	Blind River (Ontario), Canada
Brannerite	$(U,Th,Ca_2,Fe_2)Ti_2O_6$	Blind River (Ontario), Canada
Bastnaesite	$(La,Ce,Th)FCO_3$	California, USA
Pyrochlore	$(Na,Ca_2,U,Th)(Nb,Ta)_4O_{12}$	Colorado, USA
Allanite	$(Ca,Ce,Th)_2(Al,Fe,Mn,Mg)_3(SiO_4)_3OH$	Idaho and Montana, USA

Monazite is a minor constituent of heavy mineral (specific gravity greater than 3.5) concentrates mined from ancient beach placers containing approximately 3% heavy minerals (minerals of economic importance include monazite, ilmenite, garnet, rutile, zircon, sillimanite, cassiterite, and magnetite). The monazite content of the concentrate ranges from 0.5% to 1.0%, or about 0.01% to 0.03% of the placer deposit. The thorium content of monazite mineral is known to range from 0.00% to 9.0%.[3,4] The composition of monazite concentrates produced in various parts of the world is shown in Table C-II.

TABLE C-II. Composition of Monazite Concentrates

Constituent	Weight Percent India	Brazil	Florida Beach Sand	South Africa Monazite Rock	Malagasay Republic
ThO_2	8.88	6.5	3.1	5.9	8.75
U_3O_8	0.35	0.17	0.47	0.12	0.41
$(RE)_2O_3$[a]	59.37	59.2	40.7	46.41	46.2
Ce_2O_3	(28.46)	(26.8)	—	(24.9)	(23.2)
P_2O_5	0.32	0.51	4.47	4.5	—
Fe_2O_3	0.32	0.51	4.47	4.5	—
TiO_2	0.36	1.75	—	0.42	2.2
SiO_2	1.00	2.2	8.3	3.3	6.7

[a] Rare-earth oxides including Ce_2O_3.

PRODUCTION OF NUCLEAR GRADE THORIUM

The primary industrial sources of thorium are 1) monazite mineral contained in heavy mineral concentrates, normally obtained as a result of mining ancient beach placer deposits, and 2) as a by-product of processing uranium ores that also contain significant thorium credits. The following briefly discusses the technologies/facilities for mining, concentrating, extracting, purifying, and converting thorium relative to these sources.

Monazite Mineral: In the United States, placer deposits are normally mined for heavy minerals by dredging. The material loosened by the dredge is fed as a slurry to a wet mill (concentrator) that is floating behind the dredge or located at the edge of the dredge pond.[4] However, in Australia, heavy earth moving equipment is used for mining and transporting feed material to the wet mill.[2] In either case, the wet mill includes a surge bin, hammer mill, classifier screens, and parallel separation circuits. These circuits consist of a series of sluices or Humphrey spirals or both, pumps, overboard tailing discharge lines, and concentrate discharge lines. The discharged concentrate is de-watered, stockpiled, and allowed to dry to a moisture content of about 8%.

The dried concentrate is hauled to the dry mill where it is heated to remove the remaining moisture. The dry mill uses a combination of electrostatic, magnetic, and wet gravity techniques to separate the various heavy-mineral products, including the monazite sand. Monazite recovery is known to range from about 60% to about 95%, depending on the condition and type of equipment used in the dry mill.[4] The monazite sand product is then packaged and shipped to a rare-earth plant. A simplified schematic of the mining and beneficiation process is shown in Fig. C-1.

Two general methods for opening up monazite to permit extraction and separation of thorium, uranium, and rare earths are 1) reaction with hot, concentrated caustic soda solution or 2) dissolution in hot, concentrated sulfuric acid. The caustic soda process has been used on a large scale in Brazil, India, and the United States; whereas dissolution in sulfuric acid has been used in Europe and Australia.[3,4] A simplified schematic of the caustic soda process, which yields a thorium hydroxide product, is shown in Fig. C-2. A simplified schematic of the process for separating thorium, rare earths, and uranium from a sulfuric acid solution of monazite, yielding thorium nitrate product, is shown in Fig. C-3.

Other Thorium Minerals: Solvent extraction has been used commercially to recover thorium from minerals other than monazite, in which complexing by phosphate is not a problem.

In Canada, acid leaching processes used for uranium extraction dissolve up to 75% of the thorium contained in the ores. Uranium is extracted from the leach solution by ion exchange, leaving thorium, rare earth, iron, and titanium in the barren solution. Typical thorium concentrations range from 0.1 to 0.3 g ThO_2 per liter. Various solvent extraction processes were used to recover the thorium from the uranium-barren liquors. The solvent was either an alkyl phosphoric acid, or a primary amine, or an undisclosed organic phosphorus compound.[5]

At the Le Bouchet plant in France, a 33 volume percent solution of tributyl phosphate (TBP) was used in the combined extraction of thorium and uranium from a nitric acid solution of uranothorianite ore.[3]

Purification of Thorium: For nuclear applications, it is necessary to purify the thorium concentrate produced in the separation process to remove neutron-absorbing rare earths and uranium, which would isotopically dilute ^{233}U formed in thorium during subsequent irradiation. Solvent extraction with TBP (Fig. 4) is the standard procedure for purifying thorium as well as for uranium. However, the process used in different countries differs in details, as shown in Table C-III.[3]

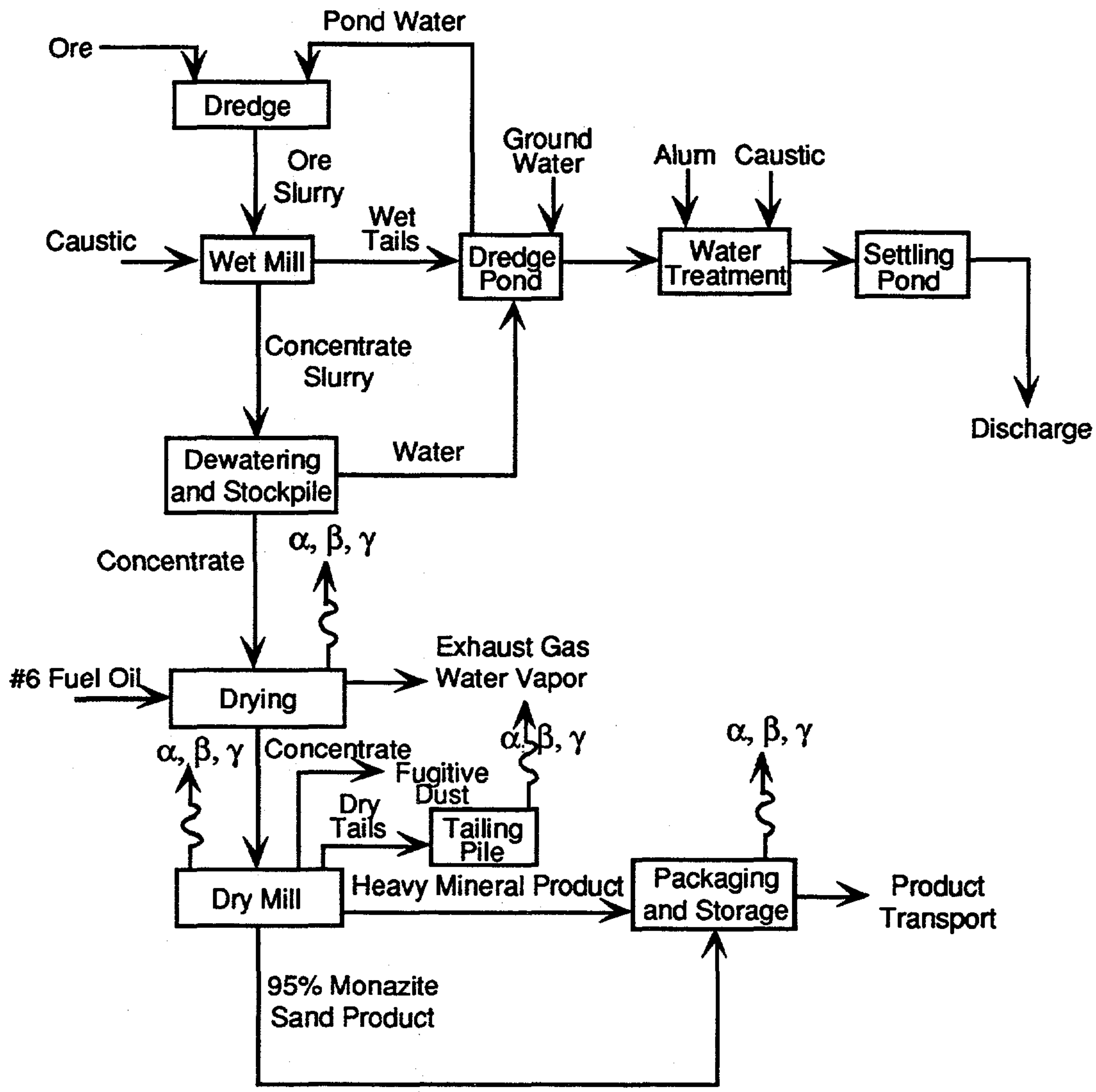

Fig. C-1. Simplified schematic diagram of mining and beneficiation of heavy minerals. (Taken from Ref. 4.)

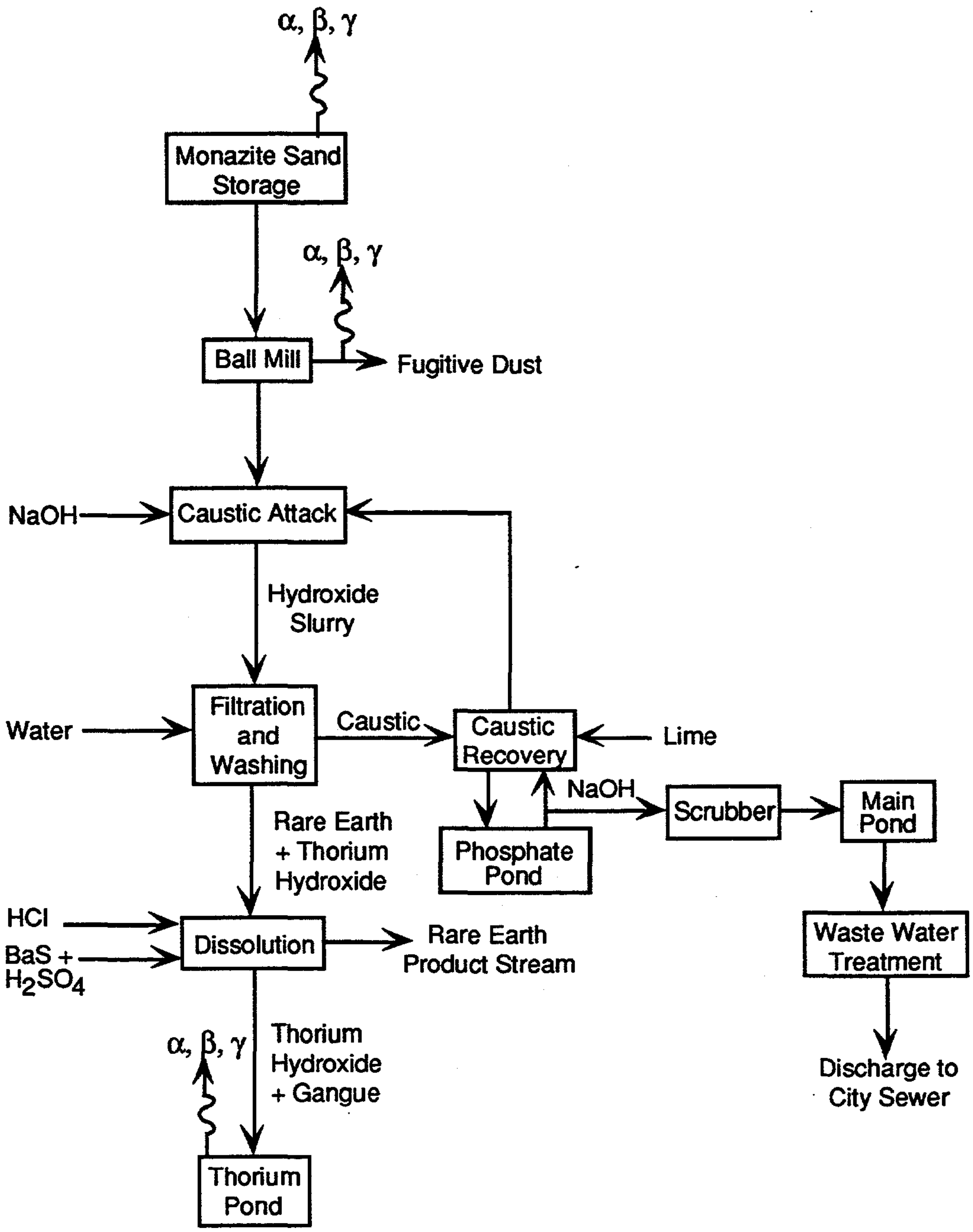

Fig. C-2. Simplified schematic of thorium extraction process. (Taken from Ref. 4.)

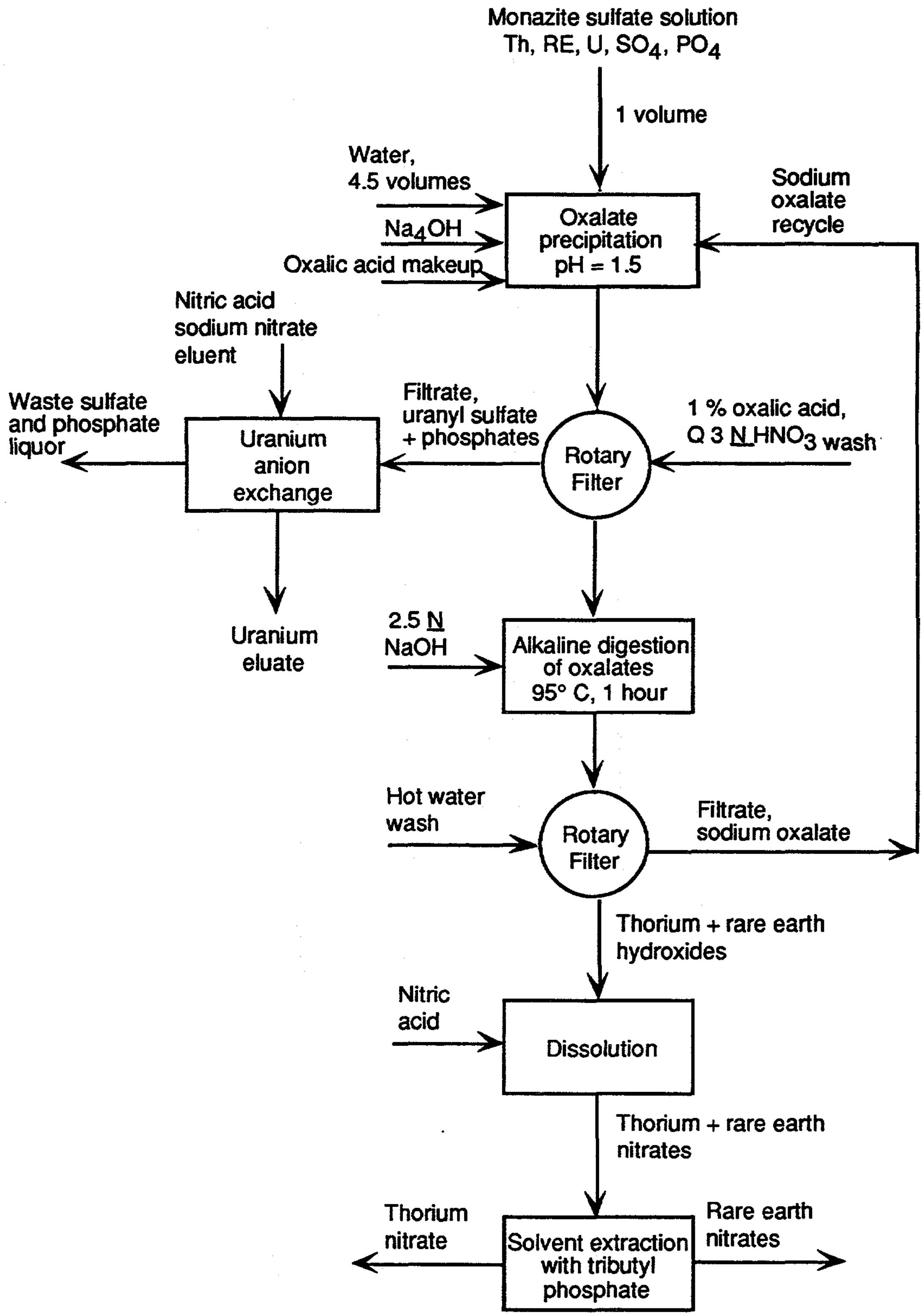

Fig. C-3. Iowa process for separating thorium, rare earths, and uranium from monazite sulfate solutions. (Taken from Ref. 3.)

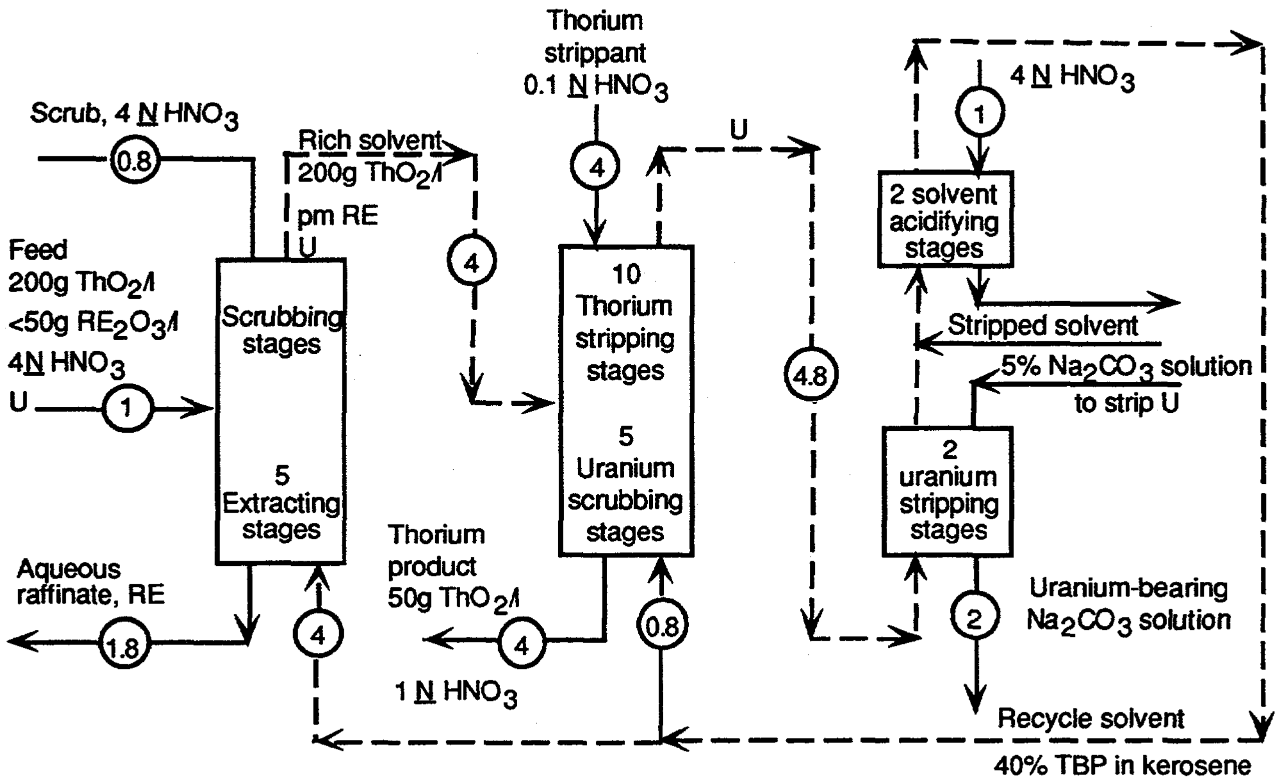

Fig. C-4. Thorium purification by solvent extraction with TBP. Circles, relative flow; —— aqueous; ---- 40% TBP in kerosene. (Taken from Ref. 3.)

TABLE C-III. Examples of Purification of Thorium on an Industrial Scale by Solvent Extraction with TBP[a]

Country	France	United Kingdom	United Kingdom	India	United States	Brazil
% TBP						
To extract uranium	—	5	40	10	—	46
To extract thorium	33	40	40	40	30	46
Diluent	Kerosene	Xylene	Kerosene	Kerosene	Solvesso 100	Varsol
Uranium strippant	—	0.02 *N* HNO_3	5% Na_2CO_3	Water	—	Na_2CO_3
Thorium strippant	Oxalic acid, to ppt. $Th(C_2O_4)_2$	0.02 *N* HNO_3	0.1 *N* HNO_3	Water	Water	4 *N* H_3SO_4, to ppt. $Th(SO_4)_2$

[a] Taken from Ref. 3.

<u>Conversion</u>: Purified thorium is usually produced in the form of an aqueous solution of thorium nitrate or crystals of hydrated thorium nitrate.

The two processes used in the United States to produce ThO_2 for use as nuclear fuel are 1) precipitation of thorium hydroxide from an aqueous solution with NH_3 (the sol-gel process) to produce fuel elements for a high-temperature gas-cooled reactor and 2) precipitation of thorium oxalate with oxalic acid, used at the AEC facility at Fernald, Ohio.[3]

Pure thorium metal must be melted in a helium or argon atmosphere or in a vacuum. Reduction of ThF_4 by calcium is the process used to produce most of the nuclear-grade thorium metal in the United States. The principal uses of ThF_4 are as an intermediate in the production of thorium metal or, potentially, as a compound in the fuel mixture of the molten-salt breeder reactor.[3] Table C-IV lists the principal processes that have been used on a semi-industrial scale to produce thorium metal.

TABLE C-IV. Principal Processes for Producing Metallic Thorium[a]

Electrolysis of fused salts
Electrolysis of $KThF_5$ in NaCl
Electrolysis of ThF_4 in NaCl/KCl
Electrolysis of $ThCl_4$ in NaCl/KCl
Reduction with Reactive Metals
Reduction of ThO_2 with Ca
Reduction of $ThCl_4$ with Mg
Reduction of ThF_4 with Ca
Thermal Dissociation of ThI_4

[a] Taken from Ref. 3.

TABLE C-V. Effluents and Waste Generated by a Typical Heavy-Mineral Placer Mining Operation[a]

Effluent/Waste	Source	Rate of Discharge	Type of Contaminant	Concentration of Contaminant	Current Control Method	Discharge Point
Mine water	Dredge pond and concentrate dewatering	700-3000 gpm	Suspended mineral and organic fine	18 × 103 - 20 × 103 mg/L	Add alum to flaculate and settle fines in holding ponds	Flow to river and evaporation to atmosphere
			Organic acids	pH ≤ 5	Add caustic to adjust pH	
			Na^+	U[b]	None	
Mill Tailings	Wet mill	511 ton/h	Fines	U	Reclaim land	Dredge pond
			Organic debris	U		
	Dry mill	6 ton/h	Monazite	0.3% - 2.1%	Recycle tailings to remove monazite (in the future)	Dry mill tailings pile
Radionuclides	Ore		Th-232 Ra-226	0.96 ± 0.02 pc/g 1.7 ± 0.1 pc/g	None	Atmosphere
	Wet mill tailings		Th-232 Ra-226	0.17 ± 0.01 pc/g 0.32 ± 0.05 pc/g		
	Ore concentrate		Th-232 Ra-226	30 ± 1 pc/g 51 ± 3 pc/g		
	95% monazite product		Th-232 Ra-226	6800 ± 100 pc/g 4800 ± 500 pc/g		
	Dry mill tailings		Th-232 Ra-226	93 ± 1 pc/g 90 ± 6 pc/g		
Fugitive dust	Dry mill	25 lb/day	Free silica Organic matter Other minerals	U	General ventilation with dilution used at one mill and induced draft with cyclone used at the other mill	Atmosphere
Gasses and smoke	Ore	U	H_2S	Noticeable odor at drudge pond	None	Atmosphere
	Dry mill	U	#6 fuel oil products of combustion	U	None	Atmosphere
	Burning bush	15 acre/mo	Smoke	U	None	Atmosphere

[a] Based on data furnished by mine operators and by the State of Florida Department of Health and Rehabilitative Services.
[b] Unknown.
Note: Taken from Ref. 4.

TABLE C-VI. Effluents and Waste Generated by a Typical Rare-Earth Processing Plant[a]

Effluent/Waste	Source	Rate of Discharge	Type of Contaminant	Concentration of Contaminant	Current Control Method	Discharge Point
Mill water discharge	Main settling pond	70 gpm average	Suspended solids	0.15 g/L average	Solids settled out pH adjusted	City sewer
			Soluble α and β activity	0.011 μCi × 10^{-4}/ml average		
			Insoluble α and β activity	0.002 μCi × 10^{-4}/ml average		
Phosphate pond water	Caustic recovery process	U[b]	Suspended β	19 pc/L	None	Evaporation to atmosphere and seepage to ground water and recycle
			Dissolved β phosphate	3 pc/L		
Thorium pond water	Monazite dissolution process	U	Suspended α	2000 pc/L	None	Evaporation to atmosphere and seepage to ground water and recycle
			Dissolved α	74 pc/L		
			Suspended β	900 pc/L		
			Dissolved β	39 pc/L		
Fugitive dust	Entire plant	U	Radionuclides	0.06 × 10^{-11} μCi/ml at NE corner of property and 0.095 × 10^{-11} μCi/ml at NW corner of property with NE wind at 5 mph. Sample at 23 cfm on Watman #40 filter	None	Atmosphere
		U	Suspended particles	U		
	Ball mill	U	Radionuclides	1.9 × 10^{-11} μCi/ml	Dust collector	Atmosphere
		U	Suspended particles	U		

TABLE C-VI (cont)

Radioactivity	Sand storage building		Gamma (γ)	15 mR/h	Restricted area	Atmosphere
	Abandoned thorium		Gamma (γ)	8-10 mR/h at 3 ft above surface	Restricted area	Atmosphere
	Active thorium pond		Gamma (γ)	0.5 mR/h	Restricted area	Atmosphere
	Soil-settling pond		Radionuclides	0.4×10^{-11} μCi/ml	Restricted area	
	Soil-field between phosphate pond and lab		Radionuclides	16×10^{-11} μCi/ml	None	
Chemical fumes	Caustic attack and dissolution	U	Caustic and acid fumes	U	Scrubber	Atmosphere

[a] Data furnished by Tennessee Department of Public Health.
[b] Unknown.
Note: Taken from Ref. 4.

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APPENDIX D

EVALUATION CRITERIA FOR SAFEGUARDS OPTIONS

A. SAFEGUARDS NEED

This criterion captures the relevance of the project to the problem of international safeguards against the proliferation of nuclear weapons. These needs are to be viewed from the perspective of the proliferation risk involved. Risk can be considered as the product of two terms: the severity of the impact of not meeting a need and the probability of occurrence of the need. For example, not detecting an underwater reprocessing plant may be a major impact, but the probability of anyone building one is quite low. Therefore, the proliferation risk is low, and the need for embracing safeguards to protect against this possibility would also be low. In general, projects dealing with the largest proliferation risks should score high. A project's score should be enhanced if it addresses multiple needs. Reviewers may obtain additional guidance on needs by examining documents from the IAEA's planning process as well as from the literature on nuclear proliferation. In developing a score for this criterion, the reviewer should answer these questions:

1. What are the most important needs addressed?
2. What is the severity of the impact of not meeting these needs?
3. What is the probability of a proliferant being detected if the need is met?

B. SUCCESS OF THE PROJECT

This criterion addresses the scientific and engineering feasibility of the project as well as the likelihood that it will lead to a product that can be successfully deployed by the end user in its intended environment. Some projects may simply lead to a product that will not work. A more likely problem is that the ultimate product of a project will not be used. Examples of this type of problem include a high cost of procurement or operation or both, unreliability, poor human-machine interface, extensive logistical requirements, failure to anticipate political or other external constraints (e.g., ES&H), or the development of a superior product by someone else. For those projects that address multiple needs, consider how successful the project will be at addressing all of these needs, not just a subset. These questions should be in the mind of the reviewer:

1. Is the project based on firm scientific principles?
2. Is the engineering required within the accepted state of the art?

3. Will the final product work in the environment intended by the proposer?
4. Can the end user afford to use the final product? (This should be used to screen for grossly expensive projects.)
5. Will the final product be too intrusive to be used?
6. Can the final product be delivered when it will be needed?
7. Are there other development projects now underway that would meet the need better or sooner or both?
8. Are there any external factors that may affect project design or practicality?

C. ENHANCEMENT OF SAFEGUARDS

A project can enhance safeguards in one of three ways: it can facilitate the expansion of safeguards into new areas, it can make traditional safeguards more effective, or it can make traditional safeguards more efficient. Because of the need to expand the international safeguards regime into new areas, some priority should be given to products that support this (e.g., detection of undeclared facilities.) However, an increase in the efficiency of traditional safeguards has the potential to release resources that can be applied to support an expanded regime. Enhancement can also be obtained by improving the effectiveness of traditional safeguards in addressing one or more needs.

Projects that fill in gaps not presently covered or provide significant improvements over current practice should score high in this category. In addition, those projects that address more than one need should receive higher scores than projects that are more narrowly focused. The reviewer should ask these questions:

1. Is the need addressed by this project already being addressed?
2. If the need is being addressed, will the project provide a significant increase in safeguards effectiveness or efficiency?
3. If the need is not being addressed, how well will the project meet the need?
4. Will the project address more than one need?
5. Will the project make a capability already available easier to use or more available?

D. R&D FACTOR

This criterion rates the R&D content of the project. The intent is not to judge the desirability of the project but rather to recognize that different funding sources may be appropriate, depending on whether a project is aimed at research, development, or implementation. Quality projects involving significant R&D efforts should be flagged for submission to other funding sources.

E. COMMENTS

Comments are an important way to include factors not captured by the normal criteria. These include such things as the desirability of combining projects, the potential for technology transfer, the possibility of supplying the item/service through a commercial vendor, and the constraints raised by any other external influences. Reviewers should feel free to provide extensive comments.

F. SCORING

Each criterion, except comment, should be scored from 0.0 to 5.0. The scores from criteria A, B, and C are to be summed to produce the Total Score. When the scores from different reviewers are tabulated, the average Total Score will be calculated. The average estimate of the R&D Factor will also be determined. Comments from reviewers will be listed with the scores.

PROJECT DESCRIPTION/OBJECTIVE FORM

Project Description:

What nonproliferation needs does the project address?

Why is it likely that this project will result in a product that will be used?

In what ways will the product of this project enhance safeguards?

INSTRUCTIONS

General Instructions: Please complete all parts of the form as completely and succinctly as possible. Your project's ranking will be based on your answers to the three questions and the clarity of your description of the project. Please do not attach an extra sheet.

What nonproliferation needs does the project address?

This question tries to capture the relevance of the project to the problem of international safeguards against the proliferation of nuclear weapons. These needs are to be viewed from the perspective of the proliferation risk involved. Risk can be considered as the product of two terms, the severity of the impact of not meeting a need, and the probability of occurrence of the need. For example, not detecting an underwater reprocessing plant may be a major impact, but the probability of anyone building one is quite low. Therefore, the proliferation risk is low, and the need for embracing safeguards to protect against this possibility would also be low. In general, projects dealing with the largest proliferation risks should score high. A project's score should be enhanced if it addresses multiple needs. You should look for guidance in developing a project by examining documents from the IAEA's planning process as well as from the literature on nuclear proliferation. In developing a score for this criterion, the reviewer will try to answer these questions:

1. What are the most important needs addressed?
2. What is the severity of the impact of not meeting these needs?
3. What is the probability of these needs actually occurring?

Why is it likely that this project will result in a product that will be used?

This question addresses the scientific and engineering feasibility of the project as well as the likelihood that it will lead to a product that can be successfully deployed by the end user in its intended environment. Some projects may simply lead to a product that will not work. A more likely problem is that the ultimate product of a project will not be used. Examples of this type of problem include a high cost of procurement or operation or both, unreliability, poor human-machine interface, extensive logistical requirements, failure to anticipate political or other external constraints (e.g., ES&H), or the development of a superior product by someone else. For those projects that address multiple needs, consider how successful the project will be at addressing all of these needs, not just a subset. These questions will be in the mind of the reviewer:

1. Is the project based on firm scientific principles?
2. Is the engineering required within the acceptable state of the art?
3. Will the final product work in the environment intended by the proposer?
4. Can the end user afford to use the final product? (This should be used to screen for grossly expensive projects.)
5. Will the final product be too intrusive to be used?
6. Can the final product be delivered when it will be needed?
7. Are there other development projects now underway that would meet the need better or sooner or both?
8. Are there any external factors that may affect project design or practicality?

<u>In what ways will the product of this project enhance safeguards?</u>

A project can enhance safeguards in one of three ways: it can facilitate the expansion of safeguards into new areas, it can make traditional safeguards more effective, or it can make traditional safeguards more efficient. Because of the need to expand the international safeguards regime into new areas, some priority should be given to products that support this (e.g., detection of undeclared facilities.) However, an increase in the efficiency of traditional safeguards has the potential to release resources that can be applied to support an expanded regime. Enhancement can also be obtained by improving the effectiveness of traditional safeguards in addressing one or more needs.

Projects that fill in gaps not presently covered or provide significant improvements over current practice should score high in this category. In addition, those projects that address more than one need should receive higher scores than projects that are more narrowly focused. The reviewer will ask these questions:

1. Is the need addressed by this project already being addressed?
2. If the need is being addressed, will the project provide a significant increase in safeguards effectiveness or efficiency?
3. If the need is not being addressed, how well will the project meet the need?
4. Will the project address more than one need?
5. Will the project make a capability already available easier to use or more available?