Fall 2013 | Winter 2014 | Spring 2014 | Summer 2014 | Volume XLII, Number 3

JNMM Journal of Nuclear Materials Management

NEW! ***ISO-CART-85 System*** from ***ORTEC***
Free-release radwaste assay goes mobile!

❶ IDM-200-V

Interchangeable Detector Module for performance versatility:

- High sensitivity: large (85 mm dia) HPGe detector, up to 2X as sensitive.
- 100% integrated portable spectrometer: electrical detector cooling, internal battery.
- ~3 hour operation on internal, swappable battery.
- Rugged design.
- Modular collimation.

❷ ISO-CART-II

New cart design for enhanced operation:

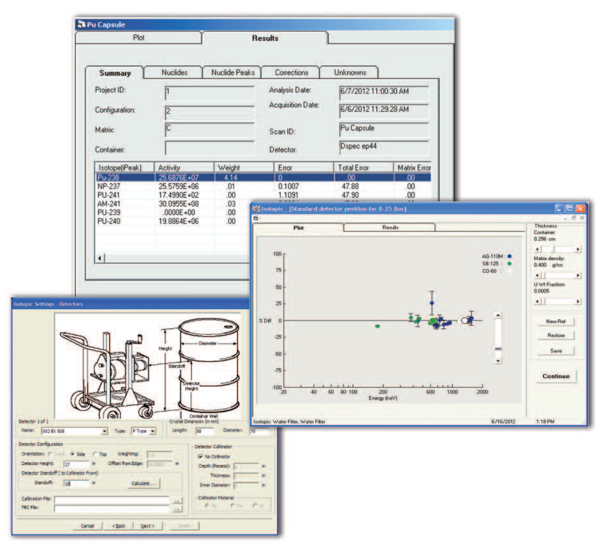
- Easy-roll cart for maneuvering over any surface.
- Adjustable track for increased stability.
- Continuous height and variable tilt adjustment.
- Disassembles to fit into a vehicle.

and:

❸ ISO-Plus Software

Proven results on thousands of real-world samples.

- Measures all common geometries: pipes, cylinders, floors, ceilings, walls, drums, boxes, and soils.
- Simple to calibrate with a single inexpensive mixed isotope point source.
- Flexible results reporting.



Practical Radwaste Solutions

801 South Illinois Ave., Oak Ridge, TN 37831-0895 U.S.A. • (865) 482-4411 • Fax (865) 483-0396 • ortec.info@ametek.com
For International Office Locations, Visit Our Website
www.ortec-online.com
ORTEC® AMETEK®

JNMM (ISSN 0893-6188) is published four times a year by the Institute of Nuclear Materials Management Inc., a not-for-profit membership organization with the purpose of advancing and promoting responsible management of nuclear materials.

DIGITAL SUBSCRIPTION RATES: Annual (United States, Canada, and Mexico) $200; single copy regular issues. $55; single copy of the proceedings of the Annual Meeting (United States and other countries) $200. Send subscription requests to *JNMM*, 111 Deer Lake Road, Suite 100, Deerfield, IL 60015 U.S.A. Make checks payable to INMM.

DISTRIBUTION and delivery inquiries should be directed to *JNMM*, 111 Deer Lake Road, Suite 100, Deerfield, IL 60015 U.S.A., or contact Anne Czeropski at +1-847-480-9573; fax, +1-847-480-9282; or e-mail, inmm@inmm.org.

JNMM Journal of Nuclear Materials Management

Topical Paper

Institute News

Departments

Bonus Content: www.inmm.org/42-3-2014

INMM
INSTITUTE OF NUCLEAR MATERIALS MANAGEMENT

Greetings to Our INMM Colleagues!

By Ken Sorenson
INMM President

We are quickly approaching the 55th INMM Annual Meeting this July in Atlanta, Georgia, USA. The Technical Program Committee has developed another promising program with 524 papers from 35 countries scheduled to be presented throughout the week. This year's Annual Meeting will have a different look and feel from previous years. Since much of the costs and revenue associated with the INMM annual operations are associated with the Annual Meeting, our budget approval process in November and Technical Program Committee meeting in March have resulted in specific format changes to the Annual Meeting. We want you to be aware of these changes before you come to Atlanta. This year, to properly manage costs, we have cut back on the "extras" so we can concentrate on what's most important: The Technical Program.

Below are some of the main changes that you will see at the 55th INMM Annual Meeting:

Enhanced: Opening Plenary Session & Panel Discussion

The Opening Plenary Session will begin with a presentation by Former U.S. Senator Sam Nunn (invited), co-chair and chief executive officer of the Nuclear Threat Initiative (NTI), and will be followed by a panel discussion on the Nuclear Security Summit moderated by INMM Vice President Larry Satkowiak. Concurrent sessions will begin at 10:40 a.m.

Changed: Speakers' Morning Meeting

This year, we ask our speakers to stop by the Speakers' Morning Meeting for a cup of coffee on the morning of their talk to meet with their session chair and hear from the Technical Program Committee Chair. *Breakfast will NOT be served.*

New in 2014: Tuesday Plenary Session

Tuesday morning will feature a plenary session presentation by IAEA Deputy Director General for the Department of Safeguards Tero Varjoranta, followed by a panel discussion on the "Evolution of Safeguards." Concurrent sessions will begin at 10:40 a.m.

Discontinued: Awards Banquet

The Awards Banquet and Cocktail Reception will not be held this year. Awards will be presented during the Opening Plenary Session on Monday.

New Time: Awards Presentation

Awards will be presented during the Opening Plenary Session on Monday. Resolutions of Respect will be presented during the Annual Business Meeting on Tuesday evening.

Discontinued: Golf Tournament and 3K Run

Our annual golf tournament and 3K run will not be held this year unless sponsors are found to entirely offset our costs.

Discontinued: New Senior/New Member Reception

We have discontinued this event for 2014. But INMM leaders will make a special point to welcome our newest members throughout the meeting.

Revamped: Student Events

Instead of the traditional Student Mixer, this year the Student Orientation and Mixer will be held in conjunction with the Student Career Fair, which will be held on Sunday night, after the President's Reception.

As always, we will kick-off the week's activities with technical division meetings on Sunday afternoon. The conference then officially begins on Monday morning. We have received more abstracts submissions this year than last year and expect to have a completely full agenda of technical presentation across the spectrum of our six Technical Divisions.

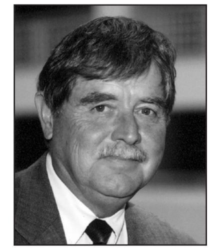
We look forward to seeing you in July in Atlanta!

Ken Sorenson, President
Larry Satkowiak, Vice President
INMM

Learn more about the
INMM 55th Annual Meeting

Download the Preliminary Program

In This Issue: Safeguardability, Navel Fuel Cycle, and Spent Fuel



By Dennis Mangan

In this issue, INMM President Ken Sorenson does a nice job summarizing some of the changes we can expect at the upcoming INMM 55th Annual Meeting, at the Atlanta Marriott Marquis July 20-24, 2014. As you are no doubt aware, the attendance at the annual meeting, because of government restrictions, is anticipated to be less than the large crowds we have had in the past. Of course, the income received from the annual meeting is the major source of operating funds for the Institute, and with a reduction in attendance, we need to reduce expenses. I know Ken and the Executive Committee struggled as they made decisions on what to eliminate or cut back. We have to express our appreciation to them for their efforts.

In this issue there are five technical articles. The first two, *The High-Reliability Safeguards Approach for Safeguardability of Remotely Handled Nuclear Facilities: 1. Functional Components to System Design* and *The High-Reliability Safeguards Approach of Remotely Handled Nuclear Facilities: 2. A Risk-Informed Approach for Safeguardability* were written by the same author, R. A. Borrelli, University of California-Berkley, Berkley, California USA, and the articles are closely related. In the first article, Borrelli proposes a potential high-reliability approach for safeguardability of advanced nuclear energy systems envisioned in a closed nuclear fuel cycle. For purposes of discussion and development, the focus is on pyroprocessing, and a high-reliability safeguards (HRS) approach is evolved. In the second article, the HRS approach is expanded by the insertion of a risk-informed approach. Funding for both of there studies was provided by the South Korean Atomic Research Institute in collaboration with the University of California-Berkley.

The third article, *Safeguarding the Military Naval Nuclear Fuel Cycle*, is authored by Sebastian Philippe, Nuclear Futures Laboratory, Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, New Jersey, USA. I personally found this article interesting, as I had never considered the ins and outs of safeguarding the military naval nuclear fuel cycle.

The last two articles, *Spent Fuel Management: Daily Challenges and Long Term Planning,* by Carlyn Greene, Ux Consulting Company, LLC (UxC), Stone Mountain, Georgia, USA, and *Spanish Scenario for Spent Fuel in Spain,* by David Garrido Quevedo, Equipos Nucleares, S.A. (ENSA), Cantabria, Spain, are also somewhat related. In the first Greene summarizes INMM's 29th Spent Fuel Seminar held in Washington, DC, USA, co-sponsored by the U.S. Nuclear Infrastructure Council (NIC).The last paper by Garrido was one of the papers presented at the seminar. Greene provides an interesting review of the Spent Fuel Seminar, addressing *Policy, Legal Perspective, The U.S. Spent Fuel Dilemma and Utility Experience.* Garrido focuses on Spain's nuclear energy program and its issues with spent fuel.

Our book reviewer Mark Maiello provides a review of *Deterring Nuclear Proliferation, The Importance of IAEA Safeguards (A Textbook)* authored by Michael Rosenthal, Leslie Fishbone, Linda Gallini, Allen Krass, Myron Kratzer, Jonathan Sanborn, Barclay Ward, and Norman Wulf. Whether you are involved in IAEA safeguards, or interested to learn about it, it appears this textbook is available online.

Jack Jekowski, chair of the INMM Strategic Planning Committee and editor of Taking the Long View, has an excellent article, as usual. It is definitely well worth it to read. He certainly gets you thinking, which is what he hopes to accomplish.

Should you have questions or comments, please feel free to contact me.

JNMM *Technical Editor Dennis Mangan can be reached via email at dennismangan@comcast.net.*

The High-Reliability Safeguards Approach for Safeguardability of Remotely Handled Nuclear Facilities: 1. Functional Components to System Design

R. A. Borrelli
University of California-Berkeley, Department of Nuclear Engineering
Berkeley, California USA

Abstract

Advanced nuclear reactor systems will use remotely handled facilities in which batch-type processing will occur in hot cells. Currently, no International Atomic Energy Agency (IAEA) safeguards criteria have been established for these facilities. Therefore, approaches to the safeguardability of these systems have been proposed by integrating IAEA safeguards with safety and physical security at the initial design stages of a commercial facility. To this end, this paper establishes a high-reliability safeguards approach in order to practically integrate proliferation resistance measures into facility design. This approach applies the safeguards-by-design concept and focuses primarily on the enhancement of intrinsic proliferation resistance measures by formulating functional design components. A commercial pyroprocessing facility is used as an example system for discussion. These components are intended to be flexible and adaptable for various conceptual designs, rather than posing a set of rigid design requirements. These are: (1) separation of process and maintenance activities, (2) verification of a clean cell after maintenance or accident, (3) initiation of a shutdown mode to halt processing activity, and (4) monitoring of material transfers. This proposed methodology also applies the extended containment and surveillance concept, where containment and surveillance measures provide the primary means of detection and materials accounting serve as defense-in-depth to restore continuity of knowledge.

Introduction

The future sustainable application of nuclear energy will require transition to a closed nuclear fuel cycle and the deployment of advanced nuclear energy systems (NESs), in order to reduce waste inventories and ensure sustainability.[1,2] Several of these will fabricate materials by batch-type, remotely handled processes in hot cells. There are no current International Atomic Energy Agency (IAEA) safeguards criteria for these facilities, and this creates many new challenges to international safeguards.[3-5] This paper then proposes a potential high-reliability safeguards (HRS) approach for the safeguardability of these facilities, focusing on the enhancement of proliferation resistance (PR) measures through facility design components that are flexible and intended to maximize common areas of risk with regards to safeguards, safety, and physical security and protection.

Motivation

Nearly 97 percent of energy resources are imported by South Korea (ROK).[6] Nuclear energy capacity is about 18.7 GWe.[7] South Korea currently operates seventeen pressurized water reactors (PWRs) and four CANDU reactors. The first ten PWR units constructed were based on the Westinghouse, Framatome (now AREVA), and Combustion Engineering (later part of Westinghouse) designs, and the remainder are based on the Korean Standard Nuclear Power Plant (KSNP+) design, contemporarily rebranded as OPR-1000. The construction of a Generation III design (APR-1400) began in 2006. Part of the motivation behind this was to develop nuclear reactor technology for export, and, in 2009, ROK secured a contract with the United Arab Emirates to build four of these reactors. Subsequently, the Korean Ministry of Knowledge Economy (MKE) stated in January 2010 that ROK will seek to increase export of nuclear power reactor technology.[8]

Used fuel inventory in ROK totaled 9,500 MTHM in 2007, stored in onsite pools. Storage capacity is expected to be exceeded by 2016.[9] Subsequently, under the National Basic Energy Plan (NEBP 2008), a "Korean Innovative, Environment Friendly, and Proliferation Resistant System for the 21st Century" (KIEP-21) concept for the recycle of used fuel by pyroprocessing and the fabrication of a metal fuel product for an advanced nuclear system was developed to address the increasing used fuel inventory.[6,11-13] "Pyroprocessing" is defined as the treatment of used uranium oxide fuel from a PWR in ceramic form to a U-TRU metallic alloy for utilization in a Generation IV reactor system through application of pyrometallurgical and electrochemical processing at high temperature.

A collaboration between the Korean Atomic Energy Research Institute (KAERI) and the University of California-Berkeley, Department of Nuclear Engineering (UCBNE) was formed in order to assess the KIEP-21 system in terms of the safeguardability of a commercial pyroprocessing facility and radiological impact of the advanced fuel cycle.[14,15] This paper then proposes the HRS concept in terms of facility design; a companion paper addresses a potential risk-informed approach for safeguardability.[16]

Objective

The HRS approach is based on the safeguards-by-design (SBD) concept.[17-22] Traditionally, the IAEA implements safeguards measures to detect the misuse, diversion, or undeclared production of special nuclear material (SNM).[23] Physical protection measures deter theft or sabotage. These fell under the purview of state programs. The implementation of safeguardability will combine international safeguards efforts, as proliferation resistance measures, with physical protection, safety, and security, equally, as part of a facility design strategy. The facility operator, state regulator, and IAEA all have important stakes in the successful design and operation of the processing facility. Because pyroprocessing activities are performed in heavily shielded hot cells, for physical protection, this provides passive barriers to SNM access. There is a lack of development in terms of PR measures for advanced NESs. It is important, therefore, to develop new methodologies because SNM composition is very different from that in contemporary aqueous recycling technologies. The proposed design strategy in this paper is meant to be flexible and adaptable and not definitive for any specific facility. During the design and initial operational phases, presumably, the lessons learned will inform a refinement of these functional components toward a more realistic design envelope. In this paper, the proposed functional components serve as a starting point for informing the initial design of a pyroprocessing facility within the context of safeguardability.

Scope

In this paper, a brief overview of pyroprocessing is first provided for use in the later discussion. Then, similarly, the SBD concept is also discussed. The HRS approach is then established, where the pyroprocessing facility is used for the discussion. Functional components to the facility design will be addressed. The conclusion addresses some practical limitations to the HRS approach and offers direction for future work.

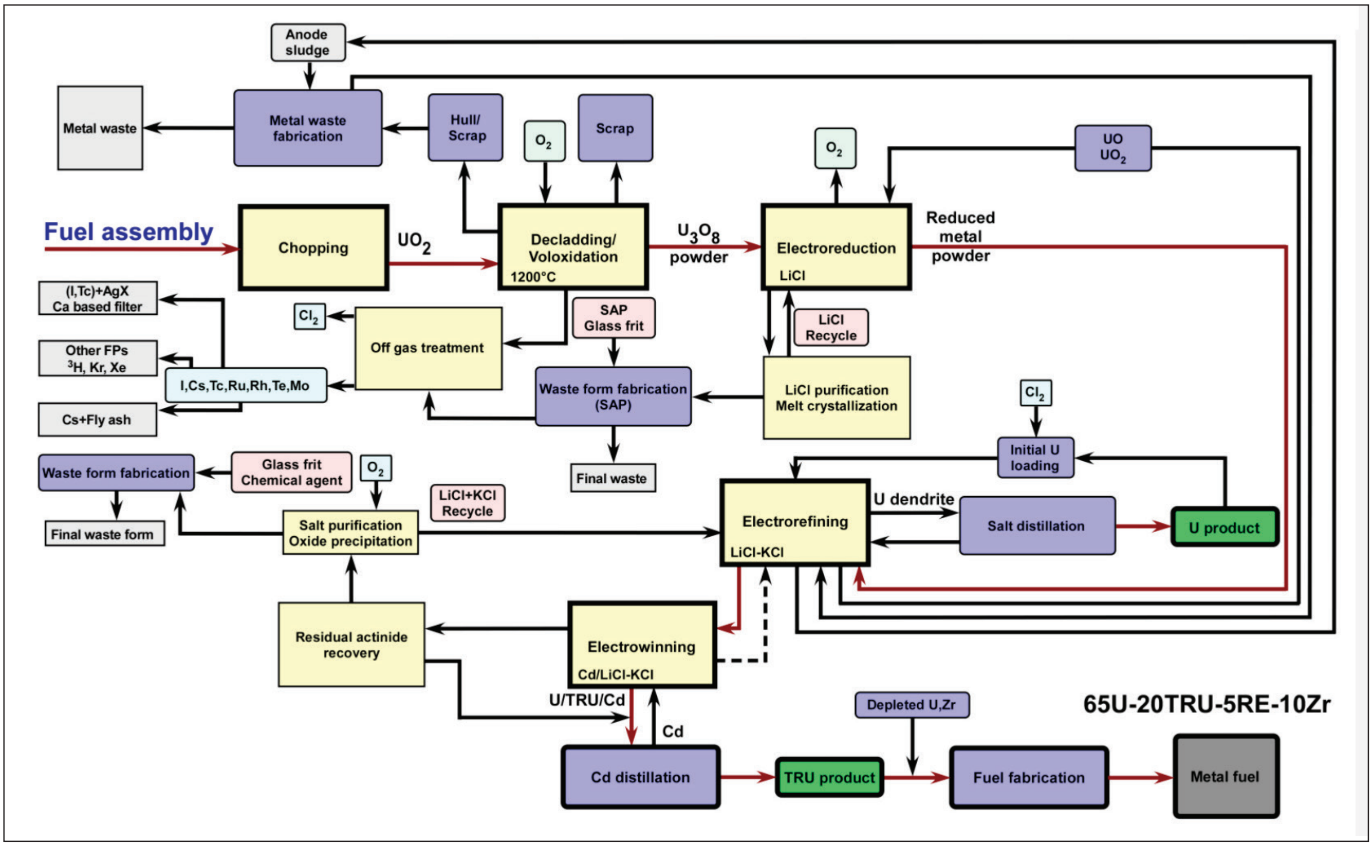
Background

Pyroprocessing

This section provides a technical overview of pyroprocessing in order to provide a basis for later discussions and further development of the HRS methodology. Pyroprocessing is an electrochemical process by which a metal fuel alloy consisting of uranium and TRU are fabricated from used uranium oxide fuel at high temperature. Materials are pyrophoric and an inert atmosphere is required. All major processes are conducted in hot cells that serve as biological shielding due to radiation levels.

Pyroprocessing research and development spans nearly half a century.[24-33] Metal fuels demonstrated the technical feasibility for advanced reactor systems in terms of meeting safety, recycling, and performance requirements on a commercial scale.[34-37] Pyroprocessing treats used UO_2 ceramic fuel and fabricates a metal fuel alloy comprised of uranium, TRU, rare earth (RE) fission products, and zirconium. The used fuel composition from a typical PWR (e.g., OPR-1000) in ROK exhibits a composition of 4.5 percent ^{235}U enrichment with 55 GWD/MTU burnup and a ten-year cooling time. Pyroprocessing has five main components: voloxidation, electroreduction, electrorefining, electrowinning, and metal fuel fabrication. Treatment of salts is also a major design consideration.[38] A schematic diagram for the material flowsheet is given in Figure 1.[39] The major processes in the system are highlighted. These processes are highlighted with thick borders and primary material flow is shown by the red arrows. Treatment and recycle of eutectic salts from the electroreduction and electrorefining processes is also a major design consideration in the KIEP-21 concept. The metal alloy fabricated by pyroprocessing exhibits a weight percent of 65U-20TRU-5RE-10Zr. This material flowsheet is for exposition purposes should be considered notional only. A

Figure 1. KIEP-21 pyroprocessing flowsheet v2.6.4: 4.5wt% 235U, 55 GWD/MTU, 10y cooling.



cold-test, engineering-scale, mock-up facility, the Pyroprocess Integrated Inactive Demonstration (PRIDE), was to be constructed by the end of 2011. The PRIDE facility will support pyroprocessing subsystems demonstration and equipment development.[40-42]

Chopping and Decladding

Whether utilizing pyroprocessing or a PUREX-type, aqueous process, this initial phase of treatment is the same. Used fuel assemblies are dismantled, fuel rods are chopped, and the rods are decladded.[43]

Voloxidation

Voloxidation converts UO_2 to U_3O_8 powder.[44,45] This results in a greater surface area that will allow for more efficient electroreduction. Voloxidation removes volatile fission products by off-gas trapping systems.[46-48]

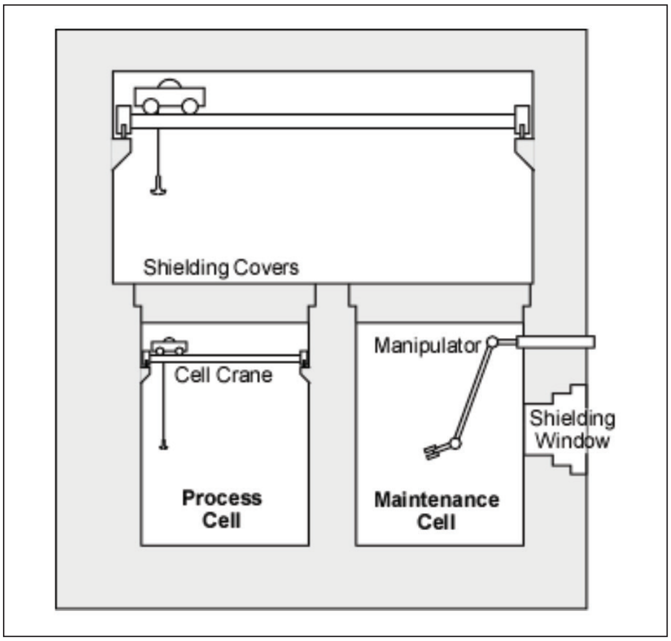
Electroreduction

Oxide powder is converted to metal by electroreduction.[30,49-53] Electroreduction utilizes a molten LiCl salt electrolyte.[38,54-59] Alkali metal and alkaline earth fission products form compounds with the chlorine in the electrolyte salt. The reduced metal product then contains uranium, TRU, and lanthanide and noble metal fission products.

Electrorefining

Electrorefining separates uranium from TRU and the remaining fission products by dissolving the electroreduced metal anodically in LiCl-KCl eutectic salt.[26,35,43,53,60-66] The salt is loaded with UCl_3 to initiate uranium deposition. Salt containing pure uranium is then collected on a solid graphite cathode. A salt distillation process recovers metal uranium.[63] Because large quantities of salt are required for practical and efficient processing, recycle is a key system design component.[38,67,68] Noble metal fission products remain on the anode. TRU and lanthanides remain in the eutectic salt.

Figure 2. .The full pyroprocessing system



Electrowinning

TRU, along with trace amounts of uranium and lanthanides, are collected on a liquid cadmium cathode.[69-73] A cadmium distillation process recovers metal TRU. Lanthanides remain in the molten salt. Additional, separate processing recycles salt and cadmium by evaporation and distillation.[61,74-76]

Metal Fuel Casting

The injection casting method has proven success in metal fuel fabrication.[25-27,31-34,37,61,77-81] Metal feedstock is melted by an induction furnace in a graphite crucible. A vacuum is induced and the molten alloy is injected into quartz molds. The molds and newly cast slugs are removed and sheared to the appropriate length. Because the molds must be broken, they are not reusable, and create a waste stream.[82] Quartz is the preferred mold material for use with Zr alloys due to a higher softening temperature.[83] In the full pyroprocessing system shown in Figure 2, the metal fuel product contains U, TRU, rare earth (RE) fission products, and zirconium, and exhibits a composition of 65U-20TRU-5RE-10Zr by weight percent.

The separation of process and maintenance activities into separate hot cells in the pyroprocessing system can reduce diversion pathways. The complex manipulations required for maintenance equipment would be performed by removing an equipment module from the process cell to the maintenance cell. When the process cell shielding blocks are removed and equipment is transferred, IAEA inspectors should be present as well as additional physical security forces. There will need to be a strong emphasis on design information verification as the maintenance procedures are implemented

TRU Losses in the Fabrication Process

The alloy left in the crucible and the casting ends that are sheared are called the "heel" and "scrap," respectively, and these can be recycled. Volatilization will cause loss of americium, due to a dominant vapor pressure over that of other TRUs.[32,34,81-86] Americium gas could be condensed for recovery, though, practically, this will be challenging, affecting cost, maintenance, and equipment reliability.

Fundamental Principles of Safeguardability

Safeguardability

The safeguardability of any nuclear facility is the extent to which facility design will readily accommodate the application of effective and cost-efficient IAEA safeguards.[3] Safeguardability is a function of the whole nuclear system, based on features of SNM, process implementation, and facility design.[5,17-19,21,22,87] Safeguardability was developed based on recent lessons learned from contemporary reprocessing facility design.[89,90] It was recommended that the safeguards approach for future processing facilities, and related components in the fuel cycle, should be optimized with safety, physical security, and facility design. This then evolved into the concept of "safeguardability" that is now widely accepted.[3]

Overview of the Safeguards-by-Design Concept

The goal of IAEA safeguards is to deter SNM diversion or misuse by the state. The state itself requires a system of nuclear material control and accountancy (MC&A) and physical security to defend against the threats of theft and sabotage by subnational actors. State-level approaches to safeguardability involve the integration of IAEA design information verification (DIV) with the state requirements for MC&A and physical security early in the design process by establishing functional design components to integrate physical security, safety, and physical protection with IAEA safeguards.[18] In this way, proliferation resistance, physical protection, safety, and security all hold equal weight as elements in the design process. The intent is to avoid retrofits for any of these considerations post-design, therefore avoiding costly overruns, regulatory violations, and operational delays.

Safeguards-by-design (SBD) provides a basis for safeguardability goals. SBD first emerged due to advancements in safety at United states defense facilities, where the U.S. Department of Energy (DOE) developed a standard based on integrating safety with physical security.[91] IAEA recognized the complementary aspects of SBD as "an approach wherein safeguards are fully integrated into the design process of a nuclear facility — from initial planning through design, construction, operation, and decommissioning."[87,91-93] SBD is especially applicable to systems where technological and engineering expertise is limited.[17-20] Practically implementing SBD requires development of systems modeling, including facility design requirements, functionality, safeguards assessment, design options, risk assessment, safeguards and security events, and life-cycle cost assessment.[17,21]

Proliferation Resistance Measures

Both proliferation resistance and physical protection are defined within the context of safeguardability.[3] Therefore, what is commonly known as international safeguards, would fall under proliferation resistance; i.e., measures to deter state-directed diversion scenarios. The state provides notification to IAEA for any facility used to handle or produce SNM.[23,89] Proliferation resistance measures provide deterrence against misuse, diversion, or undeclared production of SNM and associated technologies by the host state. This is formalized for non-nuclear weapons states through the Comprehensive Safeguards Agreement (CSA) and the Additional Protocol (AP), by which declared activities and inventories of SNM are verified with IAEA.[95-97] Optimizing proliferation resistance measures with safety and security by the state can be accomplished in a variety of ways, through a combination of intrinsic measures and extrinsic controls.[3,5,18-20,97-102] Intrinsic physical or material properties include changing SNM isotopic composition to make the material weapons-unusable, chemical barriers, or high heat due to additional radioisotope content. Engineering design incorporates relevant design features into the facility to impede diversion pathways. Multiple barriers providing defense-in-depth are preferred. Extrinsic controls inhibit the acquisition of fissile material through treaty regimes and IAEA-state agreements. Currently, there are no formal requirements on either the national or international level for integration of proliferation resistance measures with facility design.[18-20]

Proliferation Strategies

Proliferation strategies are state-level actions to acquire nuclear weapons or other explosive devices that utilize SNM by:[3] (1) concealed diversion from a declared facility, where SNM is directly removed from the facility, altered to avoid detection, or data is falsified, (2) concealed production in a clandestine facility, where SNM is produced directly, and (3) overt misuse, where a state "breaks out" to produce SNM, effectively abrogating the Nonproliferation Treaty (NPT).

Production from a clandestine facility is a potential concern for any state with the level of technical expertise required to maintain a declared program. Furthermore, the declared program can also be utilized to generate characteristic signatures of SNM processing that can mask clandestine activities. The break-out scenario potentially carries large-scale, political consequences, such as disruption of commerce or military repercussions. The probability of detection of diversion by IAEA safeguards systems provides the most important barrier to concealed acquisition of material, and barriers to break-out are derived primarily through treaty regimes.[3]

Physical Protection

Physical protection measures are efforts directed against subnational entities to acquire SNM or related technologies. This traditionally fell under the purview of a domestic safeguards program. The intent of a safeguardability methodology is to consider approaches to proliferation resistance and physical protection together with safety and security, equally, as part of a design strategy. The state develops physical protection systems to prevent or deter theft of SNM during use, storage, and transport or sabotage of nuclear facilities by subnational entities or other non-host state adversaries, by limiting and restricting routine human access to sensitive areas.[3,23] Sabotage would disrupt normal operations or cause a radiological release, and theft would include material for production of nuclear explosives or radiological dispersal devices, as well as related technical information. Adversaries could be outside groups or individuals, a combination of outsiders colluding with insiders, or insiders alone. Such events could also lead to safeguards anomalies. The Generation IV International Forum (GIF) has underscored the importance of physical protection with safeguards by defining safeguards and security in terms of physical protection robustness with proliferation resistance.[3]

Table I. IAEA standards for SNM conversion times and significant quantities

Beginning material form	Conversion time	Material	SQ
		Direct use material	
Pu, HEU, ^{233}U metal	7 – 10 days	Pu	8 kg
PuO_2 $Pu(NO_3)_4$ or other pure Pu compounds; HEU or ^{233}U oxide or other pure U compounds; MOX or other non-irradiated pure mixtures containing Pu, U(^{233}U+^{235}U ≥ 20 percent); Pu, HEU and/or ^{233}U in scrap or other miscellaneous impure compounds	1 – 3 weeks	^{233}U	
Pu, HEU, or 233U in irradiated fuel	1 – 3 months	HEU (^{235}U≥ 20 percent)	25 kg ^{235}U
U containing < 20 percent ^{235}U and ^{233}U; Th	3 – 12 months	Indirect use material	
		U (^{235}U < 20 percent)	75 kg ^{235}U 10 t natural U 20 t depleted U
		Th	20 t

Safeguards Goals

The IAEA formalizes safeguards as "the timely detection of diversion of significant quantities (SQ) of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection," where "timely detection" is based on "conversion time...required to convert different forms of nuclear material to the metallic components of a nuclear explosive device."[23] A significant quantity is "the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded." Table I contains SQs and conversion times established by IAEA.

Safeguards Metrics

Two metrics are used to determine diversion or misuse of SNM:[23,101,108] (1) The type I error or "false alarm" probability (α), where statistical analysis of accountancy data falsely concludes that SNM is missing and resolution requires IAEA investigation, and (2) The type II error or "non-detection probability" (β), commonly applied as a "detection probability" ($1 - \beta$) in that an actual diversion event is detected, given the state initiated the event.

Type I errors arise due to initiators during facility operation. These should be identified during facility design in conjunction with security systems. Type II errors are based on state-level decisions to divert. These must be rendered a strategically poor choice by the safeguards system. The IAEA currently does not have standards for the false positive anomaly, in which in the absence of diversion or misuse, the incorrect conclusion that diversion or misuse has occurred cannot be confirmed.

Classical Safeguards Approach

In a classical safeguards approach, nuclear materials accountancy (NMA) provides the primary means for timely detection of a diversion event, and containment and surveillance (C/S) measures are utilized in complement.[21,23,96] In this context, classical safeguards refers to contemporary approaches that have developed from INFCIRC/153[95] for an aqueous reprocessing facility.[96] This terminology is used in this paper to distinguish this approach with the HRS approach. The material loss, defined as material unaccounted for (MUF) is a key accounting metric for safeguards. This is derived from random measurement error, bias, and the identification of potentially falsified data by the state.[103] This is determined as the difference between the "book" inventory (the material mass that is declared) and the "physical" inventory (the material mass actually measured). The uncertainty of MUF must be within 1 SQ in order for the safeguards approach to realistically identify potential diversion of SNM or resolve an anomaly thereof. The facility is divided into various material balance areas (MBAs), where a mass balance is determined over a specified time at key measurement points (KMPs).[104,105] A critical factor for NMA is establishing an accurate baseline data cohort.

Containment and surveillance (C/S) measures include monitoring devices that visually verify nuclear materials items. That they can be implemented in an unattended mode, where data can be transmitted automatically to IAEA, is an advantage. Other measures include sealing systems or optical recording equipment to maintain physical integrity and continuity of knowledge by preventing undetected access or movement of material or equipment. C/S is the primary means for safeguards on spent fuel assemblies as these are large, bulk items for which unauthorized movement can be readily verified by stringent monitoring activities. IAEA verifies material balances of a declared facility with the state system of accounting and control (SSAC).

Importance of a National Regulatory Infrastructure for Safeguards-by-design

The state regulatory infrastructure provides extrinsic controls over facility technical specifications, quality assurance, safety and physical security, and international and domestic safeguards.[17-21] The state establishes nuclear MC&A for threats with respect to theft and sabotage by subnational entities or a rogue state. Design information verification (DIV) is submitted to IAEA for accounting compliance at the beginning of and at other times throughout facility lifetime. Safeguardability then can be achieved by identifying common goals of the national regulator, SSAC, and IAEA, with MC&A, physical protection systems, and international safeguards, as early as possible in the design phase of the facility.

High-Reliability Safeguards Methodology

Contextual Basis

Currently, there are no formally recognized or widely accepted methodologies for achieving safeguardability through safeguards-by-design. The high-reliability safeguards approach proposed here is a methodology to achieve safeguardability for a remotely handled nuclear facility. Here, the HRS approach is discussed in terms of formulating functional components to the facility to be integrated with safety, physical security, and physical protection considerations at the initial conceptual design stages. The example system discussed in this paper is a commercial pyroprocessing facility. However, no safeguards approach is comprehensive without also considering extrinsic controls. While the Comprehensive Safeguards Agreement and the Additional Protocol are existing and robust extrinsic controls, in order to achieve safeguardability, these current, and perhaps new, extrinsic controls should be integrated within the state regulatory infrastructure. For example, in the way that there are compensatory penalties for safety violations at nuclear facilities, so should a similar system be established that also includes safeguards violations. This is proposed in the companion paper,[16] where a risk-informed approach is discussed as an overall systems assessment for safeguards, safety, and security. Therefore, safeguardability is not strictly a technical problem; to achieve success, efforts must also include these extrinsic controls.

Intrinsic Materials Properties

Approaches to safeguardability will be very different for pyroprocessing than that of contemporary aqueous recycling technologies due to the material content and form. Pyroprocessing materials are in bulk form; these can be visually verified and counted, as well as weighed and assayed. The products, after electroreduction, are metal. The materials are also pyrophoric and require an inert atmosphere. They will be contained in hot cells that utilize remotely handled equipment. Therefore, for physical protection, this provides passive barriers to the theft and sabotage of SNM. In terms of material content, plutonium is not separated as a pure stream in the pyroprocessing system.

HRS Applicability to Proliferation Strategies

The HRS approach has been formulated as a methodology for the safeguardability of a declared facility. When considering the potential to pursue a weapons development program, the technological expertise of a proliferant state would have to be fairly extensive to initially consider transition to an advanced fuel cycle. This would imply that the state exhibited a fairly well-established nuclear power infrastructure. For example, this could be benchmarked for states exhibiting nuclear capacities at approximately 20 GWe, which is on par with most industrialized states with a decades-long history of nuclear power development. At this level of technical advancement, a state would also have developed a high degree of global and economic interdependence. This would also imply that a non-weapons state has developed a strong safety regime as well, including significant cooperation with IAEA. Clearly, a state at this level would be capable of overtly misusing SNM for weapons development. However, abrogation of the NPT would carry severe consequences: economically, in the form of sanctions, or withdrawal of security agreements with other states, if not outright military engagement to destroy weapons capabilities. Therefore, the industrial and technical development of any such state with intention to develop advanced nuclear system carries a form of extrinsic controls, and these barriers to break-out can be further strengthened through international agreements, such as the Additional Protocol. Therefore, effective proliferation resistance measures will include intrinsic design features, as proposed by HRS, as well as additional extrinsic controls to restrict and discourage misuse or breakout.

Extended Containment and Surveillance

Background

The extended containment and surveillance (ECS) concept features the use of C/S measures as the primary means in the safeguards approach to monitor all "credible penetrations" in a facility.[106,107] These are the technically feasible ways in which SNM could be transferred into or out of a defined MBA. ECS focuses monitoring efforts at designated KMPs. There was an attempt in the late 1970s to realize ECS as a potential approach to PUREX reprocessing plants in which existing shielding, which served as the containment barrier, was to be extended to the entirety of operations.[111,112] However, use of ECS proved difficult in this case. Credible penetrations identified for the full PUREX commercial-scale facility proved exceedingly difficult to monitor with any practical reliability due to their large number, which exceeded one thousand in total. Additionally, this would have required an IAEA inspector physical access to areas of the facility that normally would have been addressed by NMA, therefore requiring the operator to disclose potentially sensitive process data. Increased need for personnel activity within the containment boundary would have led to a higher risk for C/S anomalies. It was determined that a key feature to ECS, therefore, was to design the facility such that personnel access to these areas is very limited.

Utility of ECS to Safeguardability of Batch-processing Facilities

The ECS concept is useful as part of an approach to safeguardability for a pyroprocessing facility. Containment and surveillance measures would provide the primary means to detect misuse of SNM, while NMA would provide defense-in-depth to reestablish continuity of knowledge (COK) if an anomaly in the C/S monitoring required IAEA inspection. Because pyroprocessing involves bulk materials processed in batches, this requires the use of hot cells to serve as both shielding and containment. Personnel activity in the cells will be limited to specific and narrowly defined events as there will be no reason to enter the hot cells during normal operation. This clearly would severely limit personnel activity in sensitive areas. Because materials are in solid form, they can be counted and verified upon entrance and exit of the hot cell and MBA. During operation, therefore, the surveillance burden can be reduced provided there is confirmation that these materials remain in the hot cells during operation. This must be demonstrated to be reliably achievable and will additionally require strict monitoring of all material transfers. Credible penetrations in the pyroprocessing facility therefore should be manageable and relatively straightforward to monitor. The hot cells clearly provide physical protection barriers to access of SNM. Limiting authorization to hot cell access should also enhance security measures. Utilization of ECS to pyroprocessing safeguards can reduce pathways for undetected removal of SNM. An anomaly in the C/S monitoring systems would not singularly confirm a diversion event, and NMA techniques would still be utilized for resolution of it.

Functional Components to System Design

The HRS approach is discussed here by combining the concepts of extended containment and surveillance with safeguards-by-design to establish a robust envelope of functional components to the facility design that can be readily integrated with safety and physical security measures. The goal is to establish design options that will provide a very low rate for false alarms and false positives and high probability of detection of diversion of material. The formulation of these functional requirements is intended to be flexible to account for varying design criteria.

For the pyroprocessing facility, the hot cells provide effective radiation shielding protection, while also providing safety, physical protection, and proliferation resistance benefits by reducing possibilities for accidental releases into the environment and unauthorized and/or undetected removal of material. Remote handling and limited personnel access to the hot cells reduces the surveillance burden and any need to have multiple personnel portals for emergency access and egress. This then can improve C/S performance by reducing the need for increased personnel activity.

Separation of Process and Maintenance Activities

A major safeguards-by-design goal is to minimize diversion pathways. This can be achieved by limiting the activities available in the process cells and performing maintenance in a separate, dedicated cell. The process equipment should have a high degree of modularity; therefore, associated remote handling equipment in the process cells can be very limited in functionality. Accessibility into the process cell should also be limited. This could include the absence of windows and use shielding covers that could only be removed by a crane. Conversely, for maintenance requirements, it is important to have significant flexibility in the ability to manipulate equipment. Figure 2 provides a general schematic diagram to demonstrate a potential arrangement of the process and maintenance cells. Repairs and routine maintenance requires complex manipulations. Diversion pathways then are reduced by removing an equipment module from the process cell to the maintenance cell. Shielding blocks cannot be lifted, nor equipment removed without IAEA inspectors present. Safeguards monitoring will therefore be more straightforward regarding verifying consistency with declared operations if process equipment is modularized in order to simplify the transfer to a maintenance cell. To support this, the cells should be designed such that the number of entrance and exit portals is limited. Separation of process and maintenance functions would be only necessary for processing using TRU materials. These include off-gas treatment, separated uranium after electrorefining, treatment of fission products that are separated at several stages in the pyroprocessing scheme, and cladding hulls that are removed from the used fuel.

Material Transfers

Material transfers should be fully monitored by IAEA. This would include transfers of SNM moving in, out, or between cells. These transfers, then, by applying ECS, would be considered credible penetrations and pose a diversion pathway. Material must not be transferred therefore without first being assayed and a KMP must be established at each assay location. Design of the assay station itself should include mechanical gates that are controlled so that only one can be open at a time. An automated assay process then determines that the material is consistent with declared operation prior to the transfer. After transfer, the assay system is activated again to verify that the assay location is completely empty. Within a process cell, however, the capability to transfer materials should be severely restricted. Therefore, actual cell activities should be minimized. This concept is discussed subsequently. Transfers can be additionally monitored within a cell by doorway monitors, equipment use monitors within the cell, seals, and video surveillance.

Additionally, as part of formulating stronger extrinsic controls, it is suggested that the facility operator be required to share assay data with the IAEA as part of inventory verification or that the IAEA install proprietary monitoring equipment at these assay locations as well. This more stringent monitoring could reduce proliferation risk. Implementation of this, of course, may be problematic, though not impossible, in that IAEA monitoring would be installed in sensitive areas. Additional confidentiality agreements between the state and IAEA and incorporating such measures into the regulatory infrastructure would be needed. Monitoring material transfers within and between MBAs will be challenging. MBAs may contain multiple process cells, and many more KMPs would be needed within the MBA as well. Clearly, this will affect cost. This will also determine the location of the assay stations. This is a more long-term goal in terms of the current level of safeguardability study of the commercial pyroprocessing facility. A comprehensive systems assessment is required in order to determine how additional monitoring can minimize proliferation risk.

Secure Shutdown

Facility design for any system is based on the specification of limits in which conditions for acceptable facility operation are established and requirements for actions that must be undertaken if the facility departs from those conditions. In a nuclear reactor facility, the most important of these are when the reactor must be scrammed and the facility placed into a shutdown mode. These events not only include accidents, or external events such as an earthquake, and, for security, those that lead to any attack on the facility. Operating limits and security plans are all reviewed by the national regulatory body. Additionally, emergency procedures and inspection must be met before the restart of the facility.

This structure can also be established for the pyroprocessing facility. The safeguards systems will require similar operating limits in principle to the nuclear power facility in order to provide a sufficiently high-reliability for operation. Appropriate actions must be determined if the facility departs from these conditions. Such operating limits would include initiating events that lead to electrical power loss to safeguards systems or facility equipment, including video surveillance equipment, transfer gates, cell entry and exit portals, or major equipment malfunctions that could lead to a loss of the inert atmosphere for any of the hot cells. These would require specified mitigating actions by the operator.

In keeping with the analogy to the nuclear power facility, a safe, secure shutdown mode is suggested as part of the HRS approach. This shutdown mode would immobilize all materials and de-energize all transfer equipment in the facility. A passive seal system then could be activated to provide indication that materials immobilized in the transfer assay locations have not been moved. These should be designed to allow for monitoring from outside the radiation control area of the facility if physical access is restricted or blocked due to the consequences that initiated the shutdown mode. Recovery from the shutdown mode and subsequent restart of the facility would then require IAEA inspection in addition to emergency procedures. This would include verification that all material inventories in the system are consistent with the declared operation at the time of shutdown activation. NMA inventory data would then be needed to restore continuity of knowledge.

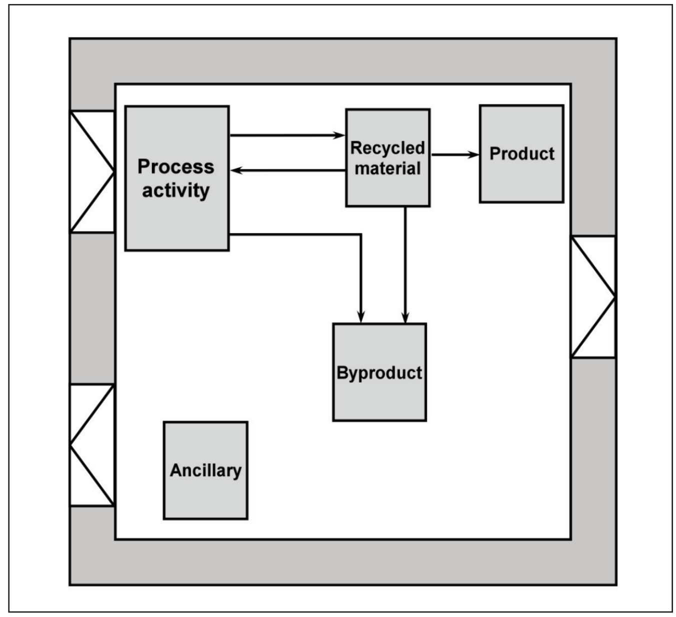
Cell Cleaning

A high level of assurance is required to demonstrate that material held up in process equipment cannot be removed from the hot cell without detection by the safeguards system. Access to the process cell should be highly restricted, but in the cases of maintenance or if the facility is placed into the secure, shutdown mode, the cell may need to be opened and entered by personnel. Before maintenance activities and transfer of equipment to the maintenance cell, all materials held up in the equipment due to normal or inadvertent causes from the process cell must be reliably monitored, quantified, and removed from the equipment. In the case of an event leading to shutdown, materials immobilized in the cell must be verified consistent with declared operations. Design information verification during maintenance will be required, particularly if it is not possible to completely remove nuclear material and verify the removal prior to opening the cell.

Idealized Process Cell Activity to Minimize Diversion Pathways

In the process cell, multiple activities will increase the risk of diversion; therefore, equipment should be limited in function. However, the process equipment and related functions in the cell will exhibit some level of sophistication in order perform the defined task. A key feature for the conceptual design then in terms of safeguardability is to consider which activities in the cell are necessary. To this end, Figure 3 contains a notional, conceptual hot cell design in which a minimum of five activities are shown. These would be necessary for the process to be completed. The process activity is of course the main function of the cell. The result would be the specific and unique product. Normal operations may result in some material that can be recycled *in situ* back to the main process activity as well as some byproduct material. The byproduct could be waste, or possibly transferred to head-end activities for additional processing. Also, ancillary activities may include chemical analysis, destructive assay, or other forms of quality control. While not completely necessary to occur in the cell, practically this may be the most appropriate place to perform them in terms of limiting diversion pathways. This idealized cell could be used as a first basis in the conceptual facility design stage in order to identify commonalities in safeguards, safety, and security.

Figure 3. Notional process cell.



Once the appropriate and necessary functions are identified, the cell design can be further refined to align with engineering practicalities and operational goals.

Electrorefining Activities

To further this discussion, Figure 4 and Figure 5 then apply this conceptual process cell design to the electrorefining (ER) and fuel fabrication (FF) processes. These were selected as examples because the electrorefiner is the first process phase where TRU is separated from other materials in the system, and the fuel fabrication process also handles the separated TRU. In Figure 4, the process activity would be the electrorefiner, where separated uranium and TRU are the intended products. The TRU/salt product will be sent to the electrowinning (EW) process in order to obtain TRU metal. Uranium metal will have to be stored until transfer to the fuel fabrication system. This is complicated since the batch sizes for ER and EW are not the same. More TRU would have to be processed than uranium in order to obtain sufficient quantities to produce commercial fuel batches. Uranium could be stored *in situ* or transferred to another storage cell. Additionally, the salt must be loaded with UCl_3. Chemical analysis may be required to test the purity of the products. Several byproducts from the ER process will occur. The graphite cathode on which the uranium metal is collected is a waste stream, as is the anode basket and resulting sludge containing noble metal fission products. Any uranium that is still present as an oxide and not fully separated is recycled to the electroreduction process. The cell design in Figure 4 shows six unidirectional transfer gates. Additional considerations regarding these will be discussed subsequently. SNM requires assay and monitoring both on entry and exit, for example, by visual inspection, neutron detection, weight, or potentially other destructive means, to complete the mass balance and insure continuity of knowledge. Equipment and salt would have to be verified clean and free of SNM prior to removal from the cell. There will be salt held up in the electrorefiner; therefore, in the case of a shutdown or for routine maintenance, this equipment will have to be cleaned and verified free of SNM in order to restart operations.

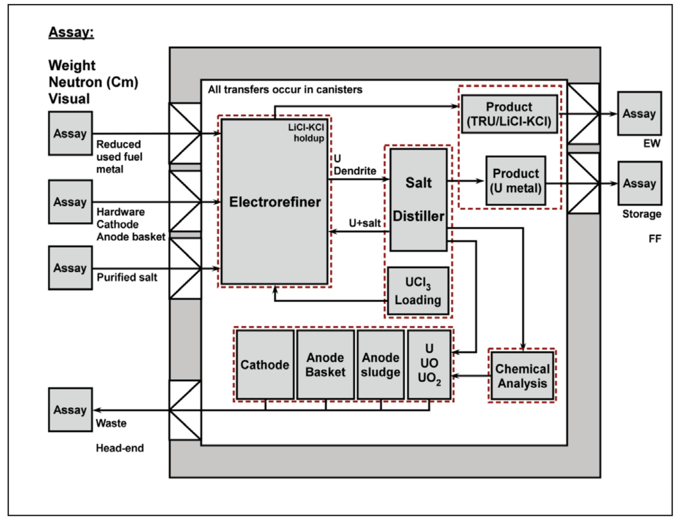
Fuel Fabrication Activities

In Figure 5, a similar notional diagram is presented for fuel fabrication. The process activity is the fabrication of the metal fuel alloy product in the form of fuel slugs obtained from the quartz molds. During the normal process, scrap, the leftover alloy from the mold trimming process, is recycled. Similarly to the ER, chemical analysis may be necessary in order to determine if the product contains the defined weight per cent of each constituent or satisfies other physical requirements, such as straightness and size. The graphite crucible in which the metals are melted is treated as waste. The heel, or coating of metal alloy on the crucible, may be collected and returned to head end processes or recycled *in situ*. The quartz molds, after being trimmed and broken to obtain the alloy, cannot be recycled and are treated as waste. For FF, monitoring is very important because the U and TRU enter separately, but after fabrication, the single-alloy product will exit the cell. These materials would have to be assayed also by visual inspection, neutron detection, weight, or potentially other destructive means. Americium will be held up in the equipment. Therefore, due to a shutdown or for routine maintenance, the melter/caster will have to be cleaned and verified free of Am. It is not currently clear whether it would be advantageous from an economic or operation perspective if the Am is recycled or disposed. The crucible will also have to be cleaned and verified free of SNM prior to disposal or to restart operations in the event of replacement due to cracking. Four unidirectional, transfer gates, are shown for this conceptual design.

Additional Design Considerations

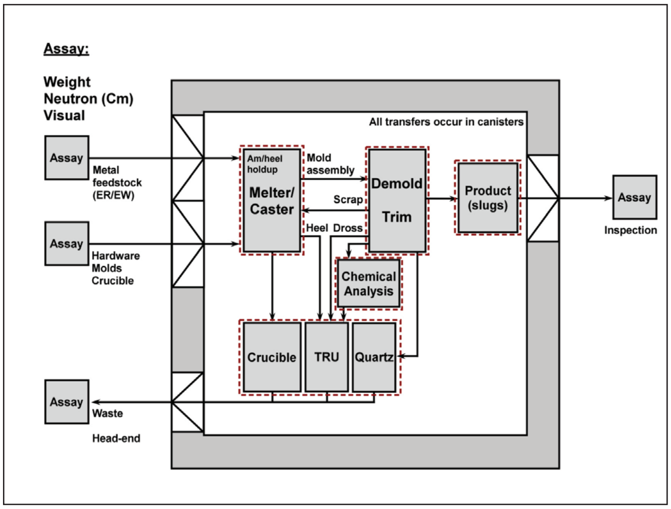
Even with the minimum process activities shown for ER and FF, the idealized process cells shown by Figure 4 and 5 are fairly

Figure 4. A notional, idealized depiction for a hot cell containing the electrorefining process (ER) is suggested. This is based on study of the KIEP-21 pyroprocessing system discussed earlier in this paper and shown in Figure 1. .



complicated and monitoring activities will be challenging. The recommended minimum five activities are contained each within the red, dotted box. The *process activity* is the electrorefiner. This separates uranium and TRU. The *recycled* material is a uranium/salt mixture. Though not technically recycled, UCl_3 is required to be initially present in the process in order to catalyze the electrochemical reactions. There are two *products*: (1) uranium metal to be stored and used later in the fuel fabrication (FF) process, and (2) TRU/salt product, which is sent to the electrowinning (EW) process in order to obtain TRU metal. Some chemical analysis, as an *ancillary* activity, may be required to test the purity of the uranium. The *byproducts* are the graphite cathode on which the uranium metal is collected. This is treated as waste. The anode basket and resulting sludge containing noble metal fission products are also treated as waste. Uranium that is still present as an oxide and not fully separated is recycled in the electroreduction process. In this process cell, there are six unidirectional, transfer gates, with the materials to be transferred are shown. Based on the ECS concept, materials containing SNM would have to be assayed, for example by visual inspection, neutron detection, weight, or potentially other destructive means. Equipment and salt would have to be verified clean and free of SNM upon entry. Material leaving the cell also requires assay and quantification in order to complete the mass balance and insure continuity of knowledge. There will be salt held up in the electrorefiner; therefore, in the case of a shutdown or for routine maintenance, this equipment

Figure 5. Notional diagram for a hot cell containing the fuel fabrication (FF) process. .



will have to be cleaned and verified free of SNM in order to restart operations. The recommended minimum five activities are contained each within the red, dotted box. The *process activity* is the injection casting system in which U, TRU/rare earth (RE), and Zr batch are melted into an alloy and injected into quartz molds to form fuel slugs. The *recycled* material (scrap) is the leftover alloy from the mold trimming process. The alloy *products* are fuel slugs that are transferred to inspection and quality control prior to fuel element assembly. Additional chemical analysis may be necessary, as an *ancillary* activity, in order to determine if the product contains the defined weight per cent of each constituent. The *byproducts* are the graphite crucible in which the metals are melted. This is treated as waste. The heel, or coating of metal alloy on the crucible, may be collected and returned to head end processes for recycle. The quartz molds, after being trimmed and broken to obtain the alloy, cannot be recycled and are treated as waste. U and TRU from the ER and EW processes must be monitored and quantified prior to loading into the melting/casting equipment. Assay of SNM both upon entry and exit is critical because U and TRU enter as separate batches, but after fabrication, the single alloy will exit the cell. These materials would have to be assayed also by visual inspection, neutron detection, weight, or potentially other destructive means. Americium will be held up in the equipment. Therefore, due to a shutdown or for routine maintenance, this melter/caster will have to be cleaned and verified free of Am. The crucible will have to be cleaned and verified free of SNM prior to disposal in order to restart operations. Four unidirectional, transfer gates, with the materials to be transferred are shown. It may not be practical from the perspective of material throughput and overall operational goals to include only one process activity per hot cell. For example, combining the electrorefining and electrowinning processes into a single cell and including an area for uranium storage may reduce overall facility cost. The number of transfers and cells would also be reduced. However, monitoring, inspection, and assay activities may become increasingly complex to verify operations are consistent with declared activity with process cells in which materials in different chemical and physical forms are entering and exiting. Overall mass flow in the facility will be affected as each of the processes in the system requires different times to complete. Batch sizes for each are also different. With no commercial or engineering facility presently operating, discussions of facility layout may be premature, as there may be physical limitations that may restrict how the process cells are constructed. The idealized process cell suggested here is intended to stimulate discussions for approaches to effectively apply HRS as well as stress that these functional components should exhibit flexibility to adapt to practical design issues.

Challenges to Facility Design

Maintenance Cells

Separating process and maintenance activities limits diversion pathways. However, because normal operations occur in an inert Ar atmosphere due to the pyrophoric nature of the materials, there will be problems with moving materials out of the cell prior to maintenance, as well as inerting the process cells again when resuming normal operations. This is also an issue when the shutdown mode is initiated. The inventory of material in the facility must be verified during inspection, which could require visual inspection or further assay within the cells. Therefore, the Ar atmosphere requires attention every time a cell requires entry.

Material Transfers

The capability to transfer materials inside the process cells should be simplified and restricted. It is suggested that materials only be transferred in canisters. The materials are in solid form, so this is feasible, and by designing these *in situ* canisters such that they can hold only a defined mass, this will also assist in monitoring on exit of the cell as well as maintaining a mass balance. It may be necessary to use a type of storage canister in the cells to contain a fixed number of batches processed in order to ease inspection and monitoring burdens when transferring materials between cells.

The number of entrance and exit portals into the process cells should be minimized to reduce inspection burdens and limit diversion pathways. However, practically, these considerations are also dependent on facility layout, or which process activities are contained within a single process cell. All of this will affect cost, as more transfer gates require additional monitoring and inspection activities. In Figure 4 and Figure 5, there are six and four transfer portals, respectively, with each for a singular purpose. This may not be practical. Use of transfer portals may be more efficient if some common activities are combined in a reasonable manner. The entry and exit portals could be combined, if all material to be processed is transferred into the cell prior to process operation, and then all of the processed material exits when the entry batches have been treated. Similarly, the equipment entry portal probably will not see frequent use and would therefore be inactive for long periods of time. These might be combined with the portals shown for exit of byproduct materials. These considerations may enhance functionality of the overall facility. It may be more important for safeguards and declared operations to have one portal through which only the main SNM process batches are transferred. This portal then would not be used for equipment or byproduct transfers. This consideration is again dependent on physical facility layout, therefore, this functional component should remain flexible as well.

Facility Layout

The physical layout of the facility will affect safety, safeguards, and physical protection and security. Many different layouts can be considered initially, where process cells are arranged in series, parallel or a related combination. This will subsequently determine placement of maintenance cells, assay locations, and transfer channels. In Figure 4 and Figure 5, an assay is shown for each transfer gate in the process cell. This may be exceedingly costly, unnecessary, and impractical. The number of assay locations, then, may be optimized dependent on the layout of the process cells as well as process activities defined for each cell. The layout will affect performance assessment of the facility both in terms of practical material throughput and operational goals. Material throughput is affected by processing and assay times, the configuration of material flows in the process cells, the batch sizes per process, recycle of byproducts to prior cells, and any required internal storage capacity to accommodate process disruptions. For example, related process cells, such as electroreduction, electrorefining, and electrowinning may be grouped together with a single assay location, while limiting entry and exit portals for SNM. These processes have different requirements for batch sizes, so there may be a need for additional storage. Similarly, for fuel fabrication and subsequent processes for fuel element assembly, these may be grouped in a different configuration because the melter/caster is designed to produce the same quantity of alloy per batch.

Figure 6. In this partial facility layout, products bearing SNM content enter and exit only through two transfer portals. (Click image to view larger version.)

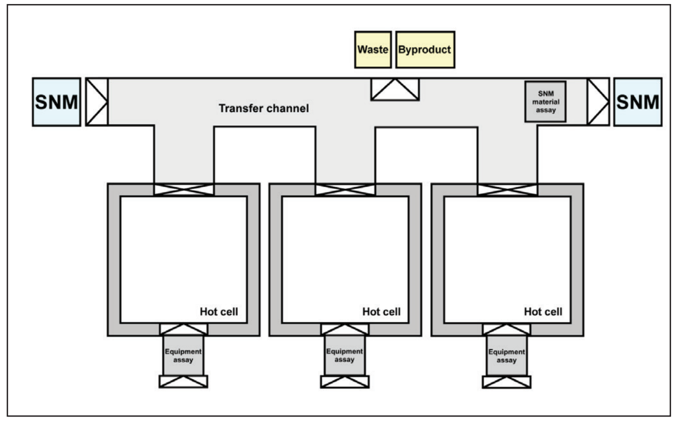
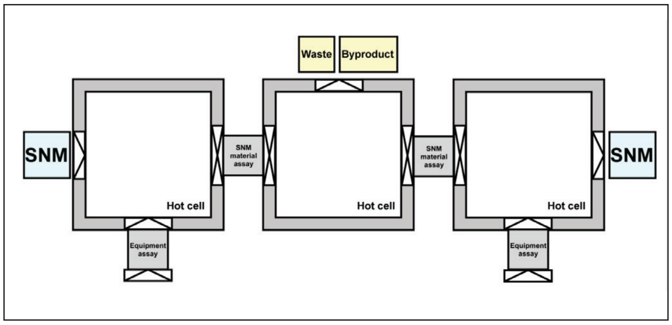


Figure 6 and Figure 7 offer possible design concepts based on these considerations. Figure 6 offers a parallel facility layout. Products bearing SNM enter and exit only through two transfer portals. This could serve as a possible layout for electroreduction, electrorefining, and electrowinning. Since these exhibit different batch sizes, one of the cells could serve as a storage buffer. A single material assay location is shown for this layout. Equipment transfers are separated from those of materials, but must exit to the assay location to be verified clean of SNM. Similarly, waste or byproducts would exit from a different portal than SNM material due to the location of further processing or waste form preparation.

Figure 7 poses a series configuration. SNM materials enter and exit through the hot cells. This configuration could serve as part of the fuel assembly process, since the subsequent sodium bonding, welding, and assembly processes are dependent on initial slug casting, whereas the head-end processes may all be conducted simultaneously. Since the melting and casting is designed to produce a fixed quantity of slugs per batch, a storage buffer would most likely be required. Equipment entry to the cells is again limited. Equipment must be assayed prior to exit to be verified clean of SNM. Waste or byproducts would exit from a different portal. For all transfers, positive control is

Figure 7. In this partial facility layout, SNM materials enter and exit through the hot cells. (Click image to view larger version.)



maintained by IAEA approval.

These are just two potential layouts out of many. Further refinement of these concepts would be dependent on the physical space for each facility; however, for developing safeguards design, these are useful for discussion and forming a direction for subsequent performance assessment approaches for the facility as a whole. The critical feature of the conceptual design approach is to remain flexible and adaptable to the different physical conditions that might be available. A single transfer channel or maintenance area may be more cost-effective; however, this causes difficulty in monitoring processed materials or delays subsequent processing if frequent transfers are required. There also may be a necessity to establish additional containment within the process cell for specific equipment. For example, the melter/caster equipment requires a vacuum seal to be established to facilitate injection of the molten alloy into the quartz molds. In the event of a pressurization accident, such containment could restrict molten metal releases in the cell. This would assist in inventory of SNM during the subsequent shutdown. The containment also provides an additional barrier to prevention of sabotage or theft. Much of these considerations are site-specific and dependent on cost. Therefore, while they should be required in the conceptual design stages of the facility, these also should be kept flexible.

Safeguards Termination

While waste management activities are not part of the HRS approach, because pyroprocessing will produce waste streams and waste forms unlike those of current aqueous processing, these should be addressed. A waste stream with significant SNM content can be diverted. For pyroprocessing, this would include all waste streams with TRU content, which result from most of the processing subsystems, whether dissolved in salt or in metallic form. The IAEA establishes that "safeguards shall terminate on nuclear material subject to safeguards upon determination by the agency that it has been consumed, or has been diluted in such a way that it is no longer usable for any nuclear activity relevant from the point of view of safeguards, or has become practicably irrecoverable."[95,108]

Establishing a practicably irrecoverable standard on waste streams as early as possible in the waste treatment processes will reduce monitoring, inspection, and accounting burdens. A technical criteria, however, is currently problematic as large-scale recycle activities for pyroprocessing have not yet been developed, and the waste streams and resulting waste forms to be emplaced in a geologic repository have not been fully characterized.

Recovery of SNM from waste will be affected by the available technologies, chemical form, concentration, and target material for recovery.[109-111] Therefore, technical criteria for safeguards termination on pyroprocessing waste streams will have to be included in agreements with the state and IAEA. In addition, for used fuel and high-level wastes, safeguards are required, even for waste emplaced in a repository.[112,113] At this time, whether this will also be required, or what technical criteria would be needed to establish termination of safeguards would only be speculative. Engineering-scale data for TRU recovery from the many recycling activities in pyroprocessing is really needed in order to make realistic judgments in this regard. However, this is still an important future issue to be addressed when establishing the commercial pyroprocessing facility safeguards.

HRS Application

The current challenge in developing a safeguardability methodology is that there are no current commercial facilities, upon which to acquire useful data cohorts. Therefore, preliminary analysis will be largely qualitative and draw upon expert judgment. This is also useful in that there is wide latitude for safeguardability development. Whether the overall goal is to produce one or several weapons, or to stockpile Pu, HRS is concerned with the diversion of SNM from a legally declared facility by the state from the commercial pyroprocessing facility. While the goal of any proliferant state then would be to acquire Pu, the unique feature of a pyroprocessing facility, however, is that Pu is not chemically separated from TRU during any processing stage. Therefore, a proliferant state would seek to obtain TRU from the legal facility and then process it elsewhere to obtain Pu. It is assumed that if the state can establish and operate a commercial pyroprocessing facility, then the state possesses the technical skills to process TRU and obtain Pu. Diversion then could occur in any of the pyroprocessing subsystems, once used fuel is converted into a metal product. Given that materials in pyroprocessing are fabricated in fixed batches, it is assumed that diversion would be protracted. Diversion of SNM on the order of kilograms of solid material would be difficult with extensive C/S measures and numerous KMPs in the facility as proposed by the HRS methodology. For physical protection, there is an advantage in that hot cells will be employed in the facility. Barring any personnel traffic during commercial processing will limit risk of theft or sabotage. Physical protection would then be important when personnel do have to enter a cell. This section presents a brief qualitative, first-level approach to considering how the HRS methodology can be applied to a pyroprocessing facility. Of course, this all will be confirmed with a rigorous systems assessment as part of future study.

Establishment of MBAs

The formation of MBAs in the facility is based upon reducing proliferation risk, but also will inform and be informed by material flow and operational goals. This is also based on the processing activities in each subsystem. This was discussed previously as the five minimum activities that would occur in each processing cell. Forming MBAs for differing facility configurations should occur early in the design stages and not as an afterthought once a facility design has been accepted. Material flow modeling would be needed for different proposed configurations in order to identify the movement of SNM in the facility.

Earlier in this paper, different cell configurations were discussed. For the fuel fabrication process, a series cell configuration may be most ideal because fuel assemblies are constructed in a sequential manner. An MBA may then be defined as the entire fuel fabrication process, from injection casting of fuel slugs to the final fuel assembly, possibly covering multiple hot cells. This is reasonable because the material, the fuel slugs themselves, do not change in chemical or physical form in the process of constructing a fuel assembly. Therefore, with accurate characterization of SNM at a KMP into this MBA, and barring entry during operation, then the SNM will be contained in the MBA and verified prior to transfer at another KMP of the completed fuel assembly. IAEA would then need access to information collected at the KMPs.

For the head-end processes in the facility, a parallel configuration may be most applicable. Both electroreduction and electrorefining operate with equal batch size. However, once the used fuel is converted to metal form by electroreduction, the material streams are split. U metal is then extracted by electrorefining and TRU metal is obtained subsequently by electrowinning. Electroreduction and electrorefining use a different salt composition as well. Therefore, because large quantities of salt will be needed for both processes, each should probably be an MBA; i.e., one for electroreduction and one for electrorefining/electrowinning. KMPs should be established at any point of salt transfer in order to verify there is no SNM in the salt prior to recycle. Additionally, the amount of TRU in an electrorefining commercial batch is small, on the order of several hundred grams. Most likely, then, the electrowinning process would not operate continually, only when a sufficient quantity of TRU has built up in the salt. Additionally, the batch size would be smaller due to criticality concerns. Therefore, with a parallel configuration of cells, the TRU-salt could be stored until ready for processing, either *in situ* or in a separate, secure storage hot cell. An MBA for this would constitute several cells. KMPs at the entry and exit of the MBA would then be needed in order to verify SNM content.

Clearly, verifying inventory is critical, as the SNM will be contained in the used metal fuel upon entry, but upon exit, there will be pure TRU metal. Operationally, since electrorefining and electrowinning process materials with different batch sizes, there is a potential for a bottleneck, which could affect downstream processes. This is also a design issue, and the material flow should be modeled as part of the conceptual design process. Finally, the fuel fabrication process will require different quantities of U and TRU metal. Therefore, storage of TRU metal is needed. Storage within the current MBA would lessen the NMA burden, where the SNM content will be verified at a KMP prior to direct transfer to a fuel fabrication MBA. The IAEA will then have access to the information collected and verified for this transfer.

Identifying Credible Penetrations

Credible penetrations are the technically feasible ways in which SNM could be transferred into and out of a defined MBA. This will provide for a more efficient facility design in that key measurement points can be identified at the conceptual design phase along with the application of appropriate C/S measures, rather than after the facility has been designed, resulting in costly retrofits and lengthy construction delays. Credible penetrations will be different depending on facility configuration and should be identified during material balance formulation. Additionally, modeling of the material flow in the facility for different facility configurations will be needed. Identifying the credible penetrations would be part of this process. However, the number of credible penetrations should also be optimized as part of the design process. With too many, the risk of diversion may increase unacceptably, while with too few, material flow and operational goals may be hindered.

For the fuel fabrication process, under the current discussion, there are relatively few credible penetrations. The entry into and exit from the MBA would clearly be two of them, and there would possibly be one or two others for equipment removal during routine maintenance or accident remediation. Presumably, personnel would access the MBA through these as well. Extensive monitoring can then be provided at KMPs located at these credible penetrations.

With the electrorefining process, however, a potential MBA may exhibit several more credible penetrations. Along with entry and exit for material transfers, the recycle and loading of salt must be considered. Salt should be transferred through a dedicated portal, separate from SNM transfers. The salt would have to be verified to be clean of SNM before exiting the MBA. There may be additional credible penetrations if TRU metal is transferred to a storage cell prior to fuel slug fabrication. Finally, there will be another credible penetration for equipment and personnel access. KMPs would be required at all of these areas.

Maintaining accurate inventory for an electrorefining and electrowinning MBA is critical for facility safeguardability because used metal fuel will enter the MBA but TRU metal will exit. It is intuitive, though speculative, that TRU metal would exhibit the highest material attractiveness in the facility, in terms of diversion, although this will be confirmed in future study. Additionally, the batch size processed by the electrowinner is different from that of the electrorefiner. Therefore, several batches of used metal fuel may enter the MBA prior to the exit of any TRU metal. SNM content must be quantified with the highest accuracy possible. KMPs are required for all these locations of credible penetrations with access by the IAEA to all monitoring information.

Cell Entry

For any subsystem in the facility, the diversion risk as well as a risk of sabotage or theft is maximized when the cell is opened for personnel entry. This will occur for routine maintenance and for accident remediation. Events that will require cell entry must be characterized by frequency as part of the systems assessment for the facility. This is beyond the scope of this current work, but it is a future goal.

For the fuel fabrication process, routine events would include replacing the graphite crucible or supplying fresh quartz molds. The crucible will contain a "heel," i.e., a coating of metal alloy. Additionally, broken molds due to trimming or accident will have to be removed, and fine metal particulates due to trimming will have to be collected along with the heel. These most likely could be recycled *in situ*. Similarly, for the electrorefining and electrowinning processes, the cathodes upon which U and TRU metal is collected would suffer from wear and will require regular replacement. These events may not require the presence of an IAEA inspector since the equipment does not require removal for either process. Therefore, entry into the cell should require a two-person rule. This is a typical and accepted practice for nuclear facilities. A two-person rule, along with KMPs established at the cell entry, can effectively enhance physical protection.

Cell Cleaning

Cell cleaning will be an important procedure within HRS for several reasons. For injection casting, replacement of the crucible will require cleaning to remove the heel. This must be performed regularly. When molds are sheared to obtain the metal alloy fuel slugs, the fine metal particulates must be collected as well. All of the SNM content in the cell must be quantified as part of declared inventory verification. A similar cleaning procedure is required in the electrowinning equipment in a potential electrorefining MBA. The liquid cadmium crucible will be replaced, but TRU metal must first be completely removed. All of these actions require regular entry into the cell.

Activity in the electrorefining MBA will also include salt removal. Additional processing of the salt is required to remove fission products for recycle back into the electrorefining and electrowinning equipment. This will also occur with some regularity, although the frequency is not currently known. The facility operator may designate fixed times for when salt removal should occur, in accordance with operational goals. Presumably, facility processing may be halted during these times, or only the head-end processes will be halted. The fuel fabrication process could continue, as there is no need for salt. The salt will have to be verified free of SNM content prior to transfer to a recycling process. This may occur within the cell, or the salt could be moved to an assay station outside the cell, but within the MBA. The recycle of salt is a major design consideration in the facility and is a focus of future study as part of the material flow process.

Events less frequent than these may require equipment removal. No equipment can be removed from the cell unless it has been cleaned and verified to be free of SNM. Recovering any possible additional SNM dispersed in the cell will also be a priority. High temperatures are necessary for processing. Failure of heating coils for either injection casting or electrorefining and electrowinning can be expected but should not be frequent as crucible replacement, for example. A similar class of events could also include failure of the motor to immerse the quartz molds into the liquid metal alloy during the injection casting process. The equipment for any of these processes may require removal from the cells in this case. Therefore, the SNM contained in the equipment must be quantified, removed, and stored securely, possibly in electronically sealed canisters, before equipment removal. The most severe and presumably most infrequent event would be loss of the inert atmosphere for any of the processes. This could result in a fire, destroying the equipment or the processed material. For this severe event, the facility shutdown must be initiated, deactivating any processing and immobilizing materials. The facility inventory must be verified and an IAEA inspection would be required prior to restarting operations. As part of the systems assessment, a licensing envelope would be assembled, and events such as this, which required the shutdown, will be identified.

Detection System for Cell Cleaning and Material Transfers

These functional components have been formulated with the intent to deter a diversion or theft when the cell is opened and entered for routine maintenance or accident remediation. However, diversion may occur during material transfer as well. A critical feature, therefore, in this methodology will be the detection system. Accurate detection and the analysis of related detection uncertainties will be needed in order to determine the probability of the false alarm as part of the system assessment for the facility.

A unique feature regarding SNM in pyroprocessing is that Pu is not chemically separated from TRU and high-heat fission products are removed early in the processing stages. Therefore, use of neutron detection of spontaneously fissioning radionuclides could be beneficial within the HRS methodology. ^{244}Cm is an overwhelmingly strong neutron emitter in used fuel. Detection of this radionuclide, then, could serve as indirect evidence of Pu. Therefore, by establishing an accurate Cm/Pu ratio, the gross neutron count could then be used for detection and mass balance calculations for Pu. While this would be a straightforward detection system, obtaining the Cm/Pu ratio with acceptable accuracy and establishing detection efficiencies that are sufficiently high will be challenging. Additionally, the detection source must be known with high confidence. This is an important design issue. Detection activity in any particular cell must not suffer from interference due to materials in adjacent cells. Therefore, cells must be designed with adequate shielding, and the arrangement of the cells in the facility must also be considered during the conceptual design phase.

Detection activities fall into two general classes currently: material transfers and in-cell cleaning, and both of these are equally important to facility safeguardability. For material transfers, the neutron detection signal recorded at a KMP, for example, leaving the electrorefining/electrowinning MBA must be equal to the signal recorded subsequently prior to entry into the fuel fabrication MBA within acceptable uncertainties. The IAEA then can verify that a legal transfer has occurred. If this is not the case, then a facility shutdown must be initiated and the potential anomaly must be resolved before operations can resume. This would apply for material balance closure and facility inventory calculations. The frequency of which must be determined based on operational goals and IAEA safeguards goals. Similarly, for any cell cleaning activities, violation of uncertainties should also predicate shutdown and inspection. Requiring that all equipment be cleaned can minimize diversion risk. Additionally, within the cell, diversion can occur by underreporting of material, such as the heel in the injection casting process. If detection must be conducted on equipment leaving the cell, then the additional material that was not reported would be identified. While the shutdown is an important part of maintaining a safeguardable facility, this must be incorporated into a state regulatory infrastructure, similar to the manner in which frequent safety violations are subject to penalties. Frequent anomalies and subsequent inspections will be costly and adversely affect operational goals. Therefore, the operator is motivated to avoid frequent shutdowns.

It is important to note that there are no formalized IAEA goals currently for pyroprocessing. Therefore, the determination of uncertainty limits is still needed. Given the functional relationship between the false alarm and detection probabilities with the significant quantity and the detection uncertainty, there can be practical study in optimizing uncertainty limits with the false alarm probability, given a fixed detection probability. Additionally, while there is a goal for the SQ for Pu at 8 kg, in the pyroprocessing facility, it will be the TRU metal that is the likely diversion target. While the critical size for a nuclear weapon does not change, and Pu is still needed to fabricate the weapon, a SQ developed for TRU metal may need to be established for the advanced fuel cycle. This will affect uncertainty limits and false alarm probability. Current studies are focused on characterizing the neutron flux for processing materials in the facility to this end.[113]

Summary Remarks and Future Directions

The sustainable use of nuclear energy will require a transition to a closed nuclear fuel cycle and the deployment of advanced systems. To that end, this paper has proposed a high-reliability safeguards (HRS) approach for demonstrating the safeguardability of remotely handled batch-processing facilities. HRS utilizes the extended containment and surveillance concept, where C/S measures provide the primary means of detection and materials accounting will serve as defense-in-depth to restore continuity of knowledge. This approach also applies the safeguards-by-design concept and focuses primarily on the enhancement of intrinsic proliferation resistance measures by the formulation of functional components suggested for facility design. These are: separation of process and maintenance activities; verification of a clean cell after maintenance or accident; initiation of a shutdown mode to halt activity; and monitoring of material transfers. These functional components are intended to be flexible and readily lend themselves to different combinations of facility layout configurations. An example pyroprocessing system was utilized for discussion.

The success of the HRS approach lies within the integration of safeguards with safety and physical security of the pyroprocessing facility. This can be potentially achieved through the licensing approach to the facility. In a subsequent paper, a risk-informed approach that can be used to assess the system in a similar manner for safety and physical security by quantifying a licensing envelope for initiating events that could lead to a safeguards anomaly will be proposed. (See page 27.) This would encompass an array of initiating events, where the probability of the false positive or false alarm error was proposed as a consequence.

Preliminary quantitative efforts are directed at modeling throughput for subsystem processes to account for material transfers, storage, and processing. Quantitative modeling regarding the amount of held-up material in process equipment also can inform the establishment of material balance areas and subsequent uncertainties in accounting.

The discussion in this paper has focused on the most important factors needed to implement this HRS approach from the design perspective. Together with the performance-based framework, this methodology can be assessed such that more practical and complex scenarios can then be generated in order to evaluate the safeguardability of remotely handled nuclear facilities.

Acknowledgements

This study was supported by funding from the Korean Atomic Energy Research Institute (KAERI) in collaboration with the University of California-Berkeley, Department of Nuclear Engineering (UCBNE).

References

1. U.S. Department of Energy and the Generation IV International Forum. 2002. A Technology Roadmap for Generation IV Nuclear Systems: Ten Nations Preparing Today for Tomorrow's Energy Needs, *GIF-002-00*.
2. Peters, M. T. 2009. *Testimony to United States House of Representatives, Committee on Science and Technology*.
3. The Proliferation Resistance and Physical Protection Evaluation Methodology Expert Group of the Generation IV International Forum. 2011. Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems, Revision 6, *GIF/PRPPWG/2011/003*.
4. Kim, H-D., H. S. Shin, and S. K. Ahn. 2010. Status and Prospect of Safeguards by Design for the Pyroprocessing Facility, *IAEA-CN-184/71*.

5. International Atomic Energy Agency. 2007. Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems, INPRO Manual – Proliferation Resistance, Volume 5 of the Final Report of Phase 1 of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), *IAEA-TECDOC-1575*.
6. Hwang, Y., M. S. Jeong, and S. W. Park. 2007. Current Status on the Nuclear Back-End Fuel Cycle R&D in Korea, *Progress in Nuclear Energy* 49, 463.
7. Choi, H-J., J. Y. Lee, and J. Choi. 2007. Development of a Korean Reference HLW Disposal System under the Korean Representative Geologic Conditions, *Proceedings of the 7th International Conference on Advanced Nuclear Fuel Cycles and Systems, Global 2007*.
8. World Nuclear Association. 2010. *Nuclear Power in South Korea*.
9. McGoldrick, F. 2009. New U.S.-ROK Peaceful Nuclear Cooperation Agreement: A Precedent for a New Global Nuclear Architecture, Center for U.S.-Korea Policy, A Project of the Asia Foundation.
10. Lee, K. J. 2008. Spent Fuel Management with Pyroprocessing: The Advantages of the Pyroprocessing Option from the Perspective of Waste Management, *KAERI Nuclearancy* 1, 8.
11. Korean Ministry of Knowledge Economy. 2008. National Energy Basic Plan 2008, *Press Release*.
12. Ko, W. I., and E-H. Kwon. 2009. Implications of the New National Energy Basic Plan for Nuclear Waste Management in Korea, *Energy Policy* 37, 3484.
13. Park, S-W., M. A. Pomper, and L. Scheinman. 2010. The Domestic and International Politics of Spent Nuclear Fuel in South Korea: Are We Approaching Meltdown? *Korea Economic Institute Academic Paper Series* 5, 1.
14. Yoon, J., and J. Ahn. 2010. A Systems Assessment for the Korean Advanced Nuclear Fuel Cycle Concept from the Perspective of Radiological Impact, *Nuclear Engineering and Technology* 42, 17.
15. Yoon, J., and J. Ahn. 2011. Performance Assessment for Korean Concept of Geological Disposal, *Proceedings of the International Conference on High-Level Radioactive Waste Management*.
16. Borrelli, R. A. 2014. A High-reliability Safeguards Approach for Safeguardability of Remotely Handled Nuclear Facilities: 2. A Risk-Informed Approach for Safeguards, *Journal of Nuclear Materials Management, Vol 42, No 3*.
17. Bean, R. S., T. A. Bjornard, and D. J. Hebditch. 2009. Safeguards-by-Design: An Element of 3S Integration, *IAEA-CN-166/067*.
18. Bjornard, T., R. Bari, D. Hebditch, P. Peterson, and M. Schanfein. 2009. Improving the Safeguardability of Nuclear Facilities, *Journal of Nuclear Materials Management* Volume 37, No. 4.
19. Bjornard, T. A., J. Alexander, R. Bean, P. C. Durst, B. Castle, S. DeMuth, M. Ehinger, M. Golay, K. Hase, D. Hebditch, J. Hockert, B. Meppen, J. Morgan, and J. Phillips. 2009. Institutionalizing Safeguards by Design: High-Level Framework, *INL/EXT-08-14777*.
20. Bjornard, T., R. Bean, P. C. Durst, J. Hockert, and J. Morgan. 2010. ImplementingSafeguards-by-Design, *INL/EXT-09-17085*.
21. Hebditch, D. J., S. J. Third, J. P. Martin, and M. Wise. 2010. International Development of Safeguards and Security by Design of Nuclear Facilities and Processes, *Proceedings of the Waste Management Symposium 2010 (WM2010).*
22. International Atomic Energy Agency. 2013. International Safeguards in Nuclear Facility Design and Construction, *IAEA Nuclear Energy Series No. NP-T-2.8*.
23. International Atomic Energy Agency. 2002. *IAEA Safeguards Glossary, International Nuclear Verification Series, No. 3*.
24. Ackerman, J. P. 1991. Chemical Basis for Pyrochemical Reprocessing of Nuclear Fuel, *Industrial& Engineering Chemistry Research* 30, 141.
25. Hofman, G. L., L. C. Walters, and T. H. Bauer. 1997. Metallic Fast Reactor Fuels, *Progress in Nuclear Energy* 31, 83.
26. Laidler, J. J., J. E. Battles, W. E. Miller, J. P. Ackerman, and E. L. Carls. 1997. Development of Pyroprocessing Technology, *Progress in Nuclear Energy,* 31, 131.
27. Walters, L. C. 1999. Thirty Years of Fuels and Materials Information from EBR-II, *Journal of Nuclear Materials* 270, 39.
28. McPheeters, C. C., R. D. Pierce, and T. P. Mulcahey. 1997. Application of the Pyrochemical Process to Recycle of Actinides from LWR Spent Fuel, *Progress in Nuclear Energy* 31, 175.
29. Crawford, D. C., D. L. Porter, and S. L. Hayes. 2007. Fuels for Sodium-Cooled Fast Reactors: US Perspective, *Journal of Nuclear Materials,* 371, 202.

30. Inoue, T., and L. Koch. 2008. Development of Pyroprocessing and Its Future Direction, *Nuclear Engineering and Technology,* 40, 183.
31. Burkes, D. E., R. S. Fielding, and D. L. Porter. 2009. Metallic Fast Reactor Fuel Fabrication for the Global Nuclear Energy Partnership, *Journal of Nuclear Materials,* 392, 158.
32. Burkes, D. E., R. S. Fielding, D. L. Porter, D. C. Crawford, M. K. Meyer. 2009. A U.S. Perspective on Fast Reactor Fuel Fabrication Technology and Experience, Part I: Metal Fuels and Assembly Design, *Journal of Nuclear Materials,* 389, 458.
33. International Atomic Energy Agency. 2011. Status and Trends of Nuclear Fuels Technology for Sodium-Cooled Fast Reactors, *IAEA Nuclear Energy Series No. NF-T-4.1*.
34. Trybus, C. L., J. E. Sanecki, and S. P. Henslee. 1993. Casting of Metallic Fuel Containing Minor Actinide Additions, *Journal of Nuclear Materials,* 204, 50.
35. Ackerman, J. P., T. R. Johnson, L. S. H. Chow, E. L. Carls, W. H. Hannum, and J. J. Laidler. 1997. Treatment of Wastes in the IFR Fuel Cycle, *Progress in Nuclear Energy* 31,141.
36. Inoue, T. 2002. Actinide by Pyro-Process with Metal Fuel FBR for Future Nuclear Fuel Cycle System, *Progress in Nuclear Energy,* 40, 547.
37. Chang, Y. H. 2007. Technical Rationale for Metal Fuel in Fast Reactors, *Nuclear Engineering and Technology,* 39, 161.
38. Song, K-C., H. Lee, J-M. Hur, J-G. Kim, D-H. Ahn, and Y-Z. Cho. 2010. Status of Pyroprocessing Technology Development in Korea, *Nuclear Engineering and Technology,* 42, 131.
39. Korean Atomic Energy Research Institute. 2010. High-Level Waste Long-Term Management Technology Development/Development of a Korean Reference Disposal System (A-KRS) for the HLW from Advanced Fuel Cycles, *KAERI/RR-3100/2009*.
40. Kim, S-H., C-H. Kim, K-H. Kim, and H-D. Kim. 2010. Study on Graphic Simulator to Analyze a Possiblity of Remote Operation for Process Equipments Using a PRIDE Digital Mockup, *Proceedings of the International Conference on Control, Automation and Systems 2010*.
41. Kim, S-H., K-H. Kim, and H-D. Kim. 2011. Analysis of Accessibility for the Remote Operation of Process Equipments in the PRIDE Digital Mockup, *Proceedings of the 11th International Conference on Control, Automation and Systems*.
42. You, G-S.,I-J. Cho, W-M. Choung, E-P. Lee, D-H. Hong, W-K. Lee, and J-H. Ku. 2011. Concept and Safety Studies of an Integrated Pyroprocess Facility, *Nuclear Engineering and Design*, 241, 415.
43. Yoo, J-H., C-S. Seo, E-H. Kim, and H-S. Lee. 2008. A Conceptual Study of Pyroprocessing for Recovering Actinides from Spent Oxide Fuels, *Nuclear Engineering and Technology,* 40, 581.
44. Goode, J. H. 1973. Voloxidation Removal of Volatile Fission Products from Spent LMFBR Fuels, *ORNL-TM-3723*.
45. Goode, J. H., and R. G. Stacy. 1978. Head-End Reprocessing Studies with H. B. Robinson-2 Fuel, *ORNL-TM-6037*.
46. Koch, L., T. Inoue, and T. Yokoo. 2005. A Safer Nuclear Fuel Management Strategy Without Sensitive Technology and Weapon Useable Material, *Proceedings of the International Conference on Advanced Nuclear Fuel Cycles and Systems GLOBAL 2005.*
47. Kim, Y.H., H. J. Lee, J. K. Lee, J. H. Jung, B. S. Park, J. S. Yoon, and S. W. Park. 2008. Engineering Design of a High-Capacity Vol-Oxidizer for Handling UO_2Pellets of Tens of Kilogram, *Journal of Nuclear Science and Technology,* 45, 617.
48. Westphal, B. R., J. J. Park, J. M. Shin, G. I. Park, K. J. Bateman, and D. L. Walquist. 2008. Selective Trapping of Volatile Fission Products with an Off-Gas Treatment System, *Separation Science and Technology,* 43, 2695.
49. Benedict, R. W., and H. F. McFarlane. 1998. EBR-II Spent Fuel Treatment Demonstration Project Status, *Radwaste Magazine* 5, 23.
50. Karell, E. J., and K. V. Gourishankar. 2001. Separation of Actinides from LWR Spent Fuel Using Molten Salt Based Electrochemical Process, *Nuclear Technology,* 136, 342.
51. Herrmann, S. D., S. X. Li, and M. F. Simpson. 2005. Electrolytic Reduction of Spent Oxide Fuel – Bench-Scale Test Results, *Proceedings of the International Conference on Advanced Nuclear Fuel Cycles and Systems, Global 2005*.
52. Sakamura, Y., M. Kurata, and T. Inoue. 2006. Electrochemical Reduction of UO_2 in Molten $CaCl_2$ or LiCl, *Journal of the Electrochemical Society,* 153, D31.
53. Benedict, R. W., C. Solbrig, B. Westphal, T. A. Johnson, S. X. Li, K. Marsden, and K. M. Goff. 2007. Pyroprocessing Progress at Idaho National Laboratory, *Proceedings of the International Conference on Advanced Nuclear Fuel Cycles and Systems, Global 2007.*

54. Westphal, B. R., D. V. Laug. 1996. Initial Cathode Processing Experiments and Results for the Treatment of Spent Fuel, *ANL/TD/CP-89650*.
55. Karell, E. J., R. D. Pierce, and T. P. Mulcahey. 1996. Treatment of Oxide Spent Nuclear Fuel Using the Lithium Reduction Process, *ANL/CMT/CP-89562, Argonne National Laboratory*.
56. Shin, Y. J. et al. 2000. Development of Advanced Spent Fuel Management Process, *KAERI/RR-2128/2000*.
57. Usami, T., M. Kurata, T. Inoue, and J. Jenkins. 2000. Behavior of Actinide Elements in the Lithium Reduction Process(I) – Feasibility of the Li Reduction Process to UO_2 and PuO_2, *Komae Research Laboratory Report*, *T-99089*.
58. Hur, J. M., I. K. Choi, S. H. Cho, S. M. Jeong, and C. S. Seo. 2008. Preparation and Melting of Uranium from U_3O_8, *Journal of Alloys and Compounds* 452, 23.
59. Park, B. H., I. W. Lee, and C. S. Seo. 2008. Electrolytic Reduction Behavior of U_3O_8 in a Molten LiCl-Li_2O Salt, *Chemical Engineering Science* 63, 3485.
60. Tomczuk, Z., J. P. Ackerman, R. D. Wolson, and W. E. Miller. 1992. Uranium Transport to Solid Electrodes in Pyrochemical Reprocessing of Nuclear Fuel, *Journal of the Electrochemical Society,* 139, 3523.
61. Iizuka, M., T. Koyama, N. Kondo, R. Fujita, and H. Tanaka. 1997. Actinides Recovery from Molten Salt/Liquid Metal System by Electrochemical Methods, *Journal of Nuclear Materials,* 247, 183.
62. Koyama, T., M. Iizuka, Y. Shoji, R. Fujita, H. Tanaka, T. Kobayashi, M. Tokiwai. 1997. An Experimental Study of Molten Salt Electrorefining of Uranium Using Solid Iron Cathode and Liquid Cadmium Cathode for Development of Pyrometallurgical Reprocessing, *Journal of Nuclear Science and Technology,* 34, 384.
63. Lee, J-H., Y-H. Kang, S-C. Hwang, J-B. Shim, B-G. Ahn, E-H. Kim, and S-W. Park. 2006. Electrodeposition Characteristics of Uranium in Molten LiCl–KCl Eutectic and Its Salt Distillation Behavior, *Journal of Nuclear Science and Technology,* 43, 263.
64. Lee, J. H., Y. H. Kang, S. C. Hwang, H. S. Lee, E. H. Kim, and S. W. Park. 2008. Electrorefining Concept for a Spent Metallic Nuclear Fuel-I: Computational Fluid Dynamics Analysis, *Nuclear Technology,* 162, 107.
65. Lee, J. H., Y. H. Kang, S. C. Hwang, J. B. Shim, E. H. Kim, and S. W. Park. 2008. Application of Graphite as a Cathode Material for Electrorefining of Uranium, *Nuclear Technology,* 162, 135.
66. Lee, J. H., K. H. Oh, Y. H. Kang, S. C. Hwang, H. S. Lee, J. B. Shim, E. H. Kim, and S. W. Park. 2009. Assessment of a High-Throughput Electrorefining Concept for a Spent Metallic Nuclear Fuel-II: Electrohydrodynamic Analysis and Validation, *Nuclear Technology,* 165, 370.
67. Kim, E. H., G. I. Park, Y. Z. Cho, and H. C. Yang. 2008. A New Approach to Minimize Pyroprocessing Waste Salts through a Series of Fission Product Removal Process, *Nuclear Technology,* 162, 208.
68. Eun, H. C., H. C. Yang, H. S. Lee, and I. T. Kim. 2009. Distillation and Condensation of LiCl-KCl Eutectic Salts for a Separation of Pure Salts Form Salt Wastes from an Electrorefining Process, *Journal of Nuclear Materials,* 395, 58.
69. Ackerman, J. P., and J. L. Settle. 1993. Distribution of Plutonium, Americium, and Several Rare Earth Fission Product Elements between Liquid Cadmium and Licl-Kcl Eutectic, *Journal of Alloys and Compounds,* 199, 77.
70. Roy, J. J., L. F. Grantham, D. L. Grimmett, S. P. Fusselman, C. L. Krueger, T. S. Storvick, T. Inoue, Y. Sakamura, and N. Takahashi. 1996. Thermodynamic Properties of U, Pu, Pu, and Am in Molten LiCl-KCl Eutectic and Liquid Cadmium, *Journal of the Electrochemical Society,* 143, 2487.
71. Kinoshita, K., T. Inoue, S. P. Fusselman, D. L. Grimmett, J. J. Roy, R. L. Gay, C. L. Krueger, C. R. Nabelek, and T. S. Storvivk. 1999. Separation of Uranium and Transuranic Elements from Rare Earth Elements by Means of Multistage Extraction in LiCl – KCl/Bi System, *Journal of Nuclear Science and Technology,* 36, 189.
72. Iizuka, M., K. Uozumi, T. Inoue, T. Iwai, O. Shirai, and Y. Arai. 2001. Behavior of Plutonium and Americium at Liquid Cadmium Cathode in Molten LiCl-KCl Electrolyte, *Journal of Nuclear Materials,* 299, 32.
73. Kwon, S. W., D. H. Ahn, E. H. Kim, and H. G. Ahn. 2009. A Study on the Recovery of Actinide Elements from Molten LiCl–KCl Eutectic Salt by an Electrochemical Separation, *Journal of Industrial and Engineering Chemistry,* 15, 86.
74. Ali, S. T., J. V. Rao, K. S. Varma, and T. L. Prakash. 2002. Purification of Cadmium up to 5N+ by Vacuum Distillation, *Bulletin of Materials Science,* 25, 479.

75. Kato, T., M. Iizuka, T. Inoue, T. Iwai, and Y. Arai. 2005. Distillation of Cadmium from Uranium–Plutonium–Cadmium Alloy, *Journal of Nuclear Materials,* 340, 259.
76. Westphal, B. R., J. C. Price, D. Vaden, and R. W. Benedict. 2007. Engineering-Scale Distillation of Cadmium for Actinide Recovery, *Journal of Alloys and Compounds,* 444-445,561.
77. Pahl, R. G., D. L. Porter, C. E. Lahm, and G. L. Hofman. 1990. Experimental Studies of U-Pu-Zr Fast Reactor Fuel Pins in the Experimental Breeder Reactor-II, *Metallurgical Transactions A,* 21A, 1863.
78. Inoue T., and H. Tanaka. 1997. Recycling of Actinides Produced in LWR and FBR Fuel Cycles by Applying Pyrometallurgical Process, *Proceedings of the International Conference on Advanced Nuclear Fuel Cycles and Systems 1997*.
79. Ogata, T., and T. Tsukada. 2007. Engineering-Scale Development of Injection Casting Technology for Metal Fuel Cycle, *Proceedings of the International Conference on Advanced Nuclear Fuel Cycles and Systems,* *Global 2007*.
80. Meyer, Mitchell K. 2009. A U.S. Perspective on Fast Reactor Fuel Fabrication Technology and Experience, Part I: Metal Fuels and Assembly Design, *Journal of Nuclear Materials,* 389, 458.
81. Meyer, M. K., S. L. Hayes, W. J. Carmack, and H. Tsai. 2009. The EBR-II X501 Minor Actinide Burning Experiment, *Journal of Nuclear Materials,* 392, 176.
82. Meyer, M. K., S. L. Hayes, J. R. Kennedy, D. D. Keiser, B. A. Hilton, S. M. Frank, Y. S. Kim, G. S. Chang, and R. G. Ambrosek. 2003. Development and Testing of Metallic Fuels with High Minor Actinide Content, *Proceedings of the 11th International Conference on Nuclear Engineering* (*ICONE-11*).
83. Wu, X., R. Clarksean, Y. Chen, and M. K. Meyer. 2002. Design and Analysis for Melt Casting Metallic Fuel Pins, *Proceedings of the International Congress on Advanced Nuclear Power Plants.*
84. Erway, N. D., and O. C. Simpson. 1950. The Vapor Pressure of Americium, *Journal of Chemical Physics,* 18, 953.
85. Marsden, K. 2007. Report on Development of Concepts for the Advanced Casting System in Support of the Deployment of a Remotely Operable Research Scale Fuel Fabrication Facility for Fuel, *INL/EXT-07-12469*.
86. Keiser, D. D., Jr., J. R. Kennedy, B. A. Hilton, and S. L. Hayes. 2008. The Development of Metallic Nuclear Fuels for Transmutation Applications: Materials Challenges, *Journal of Metals* (*JOM*), 60, 29.
87. International Atomic Energy Agency. 2008. *20/20 Vision for the Future, Background Report by the Director General for the Commission of Eminent Persons*.
88. International Atomic Energy Agency. 2012. INPRO Collaborative Project: Proliferation Resistance: Acquisition/Diversion Pathway Analysis (PRADA), *IAEA-TECDOC-1684*.
89. Ehinger, M. H., and S. J. Johnson. 2009. Lessons Learned in International Safeguards - Implementation of Safeguards at the Rokkasho Reprocessing Plant, *ORNL/TM-2010/23*.
90. Johnson, S. J., Ehinger, M. H. 2010. Designing and Operating for Safeguards: Lessons Learned from the Rokkasho Reprocessing Plant (RRP), *PNNL-19626*.
91. U.S. Department of Energy. 2008. Standard: Integration of Safety into the Design Process, *DOE-STD-1189-2008*.
92. International Atomic Energy Agency. 2008. *Reinforcing the Global Nuclear Order for Peace and Prosperity – Role of the IAEA to 2020 and Beyond, Report by Independent Commission at the Request of the Director General*.
93. International Atomic Energy Agency. 2009. Facility Design and Plant Operation Features that Facilitate Implementation of IAEA Safeguards, *SGCP-CCA, STR-360*.
94. International Atomic Energy Agency. 1970. Treaty on the Nonproliferation of Nuclear Weapons, *INFCIRC/140*.
95. International Atomic Energy Agency. 1972. The Structure and Content of Agreements between the Agency and states Required in Connection with the Treaty on the Nonproliferation of Nuclear Weapons, *INFCIRC/153 (Corrected)*.
96. International Atomic Energy Agency. 1997. Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency for the Application of Safeguards, *INFCIRC/540 (Corrected)*.
97. Bragin, V., J. Carlson, and R. Leslie. 2001. Integrated Safeguards: Status and Trends, *The Nonproliferation Review,* 8, 102.
98. Feiveson, H. 2001. The Search for Proliferation Resistant Nuclear Power, *Journal of the Federation of American Scientists,* 54, 1.

99. Bragin V.,J. Carlson, R. Leslie, R. Schenkel, J. Magill, and K. Mayer. 2007. Proliferation Resistance and Safeguardability of Innovative Nuclear Fuel Cycles, *IAEA-SM-367/15/07*.
100. Pomeroy, G., R. Bari, E. Wonder, M. Zentner, E. Haas, T. Killeen, G. Cojazzi, and J. Whitlock. 2008. Approaches to Evaluation of Proliferation Resistance of Nuclear Energy Systems, *Proceedings of the 49th Annual Meeting of the Institute of Nuclear Materials Management*.
101. Sevini, F., G. Renda, and V. Sidlova. 2011. A Safeguardability Check-List for Safeguards-by-Design, *ESARDA Bulletin,* 46, 79.
102. International Atomic Energy Agency. 2002. Proliferation Resistance Fundamentals for Future Nuclear Energy Systems, *IAEA STR-332*.
103. Avenhaus, R. 1977. *Material Accountability: Theory, Verification, Applications*. New York: John Wiley & Sons.
104. Goldman, Aaron S., Richard R. Picard, and James P. Shipley. 1982.Statistical Methods for Nuclear Materials Safeguards: An Overview, *Technometrics,* 24, 267.
105. Beedgen, R., and R. Seifert. 1998. Statistical Methods for Verification of Measurement Models, *ESARDA Bulletin,* 15, 5.
106. International Nuclear Fuel Cycle Evaluation. 1979. PIPEX-A Model of a Design Concept for Reprocessing Plants with Improved Containment and Surveillance Features, *INFCE/DEP./WG.4/64*.
107. Lovett, J. E. 1987. Nuclear Materials Safeguards for Reprocessing, *IAEA-STR-151/152*.
108. International Atomic Energy Agency. 1968. The Agency's Safeguards System (1965, as provisionally extended in 1966 and 1968), *INFCIRC/66/Rev. 2*.
109. International Atomic Energy Agency. 1990. Consultants' Report on Meeting for Development of Technical Criteria for Termination of Safeguards for Material Characterized as Measured Discards, *STR-251, Rev. 2*.
110. Pattah, A., and N. Khlebnikov. 1991. A Proposal for Technical Criteria for Termination of Safeguards for Materials Characterized as Measured Discards, *Journal of Nuclear Materials Management,* Volume 19, No. 2.
111. Larrimore, J. 1995. Termination of International Safeguards on Nuclear Material Discards: An IAEA Update, *Proceedings of the 40thAnnual Meeting of the Institute of Nuclear Materials Management*.
112. Linsley, G., and A. Fattah. 1994. The Interface between Nuclear Safeguards and Radioactive Waste Disposal: Emerging Issues, *IAEA Bulletin,* 36, 22.
113. Peterson, P. F. 1996. Long-Term Safeguards for Plutonium in Geologic Repositories, *Science and Global Security,* 6, 1.
114. Borrelli, R. A. 2013. Use of Curium Spontaneous Fission Neutrons for Safeguardability of Remotely Handled Facilities: Fuel Fabrication in Pyroprocessing, *Nuclear Engineering and Design*, http://dx.doi.org/10.1016/j.nucengdes.2013.03.025.

The High-Reliability Safeguards Approach for Safeguardability of Remotely Handled Nuclear Facilities: 2. A Risk-Informed Approach for Safeguardability

R. A. Borrelli
University of California-Berkeley, Department of Nuclear Engineering
Berkeley, California USA

Abstract

The safeguardability of an advanced nuclear energy system can be achieved by implementing International Atomic Energy Agency safeguards at the initial facility design stages. In a companion paper (see page 4), a high-reliability safeguards (HRS) approach was introduced, where an envelope of functional components was proposed as part of a design strategy for a remotely handled fuel fabrication facility. Discussion was then based on a commercial pyroprocessing facility as an example system. The functional components are intended to be flexible and adaptable for various conceptual designs.

Here, the HRS methodology is further developed by considering how safeguardability can be integrated into a licensing approach. Primarily, within this context, then, a risk-informed, performance based-framework is qualitatively discussed. Potential initiators of diversion strategies that could arise from similar classes of events as that of safety and physical security are identified and their frequency of occurrence are formulated. This can then be utilized to assess system components by quantifying a licensing envelope that will encompass a spectrum of initiating events ranging from low-frequency normal operational occurrences to higher-frequency off-normal and security-related events that also challenge physical protection of the facility. The consequence of which, for safeguards, would be the probability of a false alarm or false positive anomaly. This framework is adaptable for incorporating additional engineering experience as it becomes available, and should also be applicable to similar remotely-handled facilities.

Introduction

Advanced nuclear energy systems (NESs) are needed for the future sustainable use of nuclear energy.[1,2] These will employ facilities where materials are fabricated by batch-type, remotely handled processes in hot cells. There are no current International Atomic Energy Agency (IAEA) safeguards criteria for these facilities, and this creates many new challenges to international safeguards.[3,4] Previously, a high-reliability safeguards (HRS) was proposed for the safeguardability of such facilities.[5] Functional components to facility design were suggested in order to maximize common areas of risk with regards to safeguards, safety, and physical security and protection. Subsequently, in this paper the HRS methodology is further developed.

1.1. Motivation

This paper is the result of a collaboration between the Korean Atomic Energy Research Institute (KAERI) and the University of California-Berkeley, Department of Nuclear Engineering (UCBNE), as part of a systems assessment for the Korean advanced fuel cycle concept (KIEP-21) in which used fuel from light water reactors (LWRs) is treated by pyroprocessing for use in an advanced NES. "Pyroprocessing" is defined as the treatment of used uranium oxide fuel from an LWR in ceramic form to a U-TRU metallic alloy for utilization in a Generation IV reactor system through application of pyrometallurgical and electrochemical processing at high temperature.

The collaboration was formed in order to assess the KIEP-21 system in terms of the safeguardability of a commercial pyroprocessing facility and radiological impact of the advanced fuel cycle.[6,7] Due to the dwindling storage capacity for used fuel in the Republic of Korea (ROK), the advanced fuel cycle concept was developed to address this as directed by national government energy policy (NEBP 2008).[5,8-13]

Objective

The HRS approach is based on the concept of safeguards-by-design (SBD).[14-18] Proliferation resistance and physical protection measures are incorporated into facility design concepts, equally weighted with safety and physical security concerns. This has not been previously done, resulting in safeguards-related retrofits that led to long delays and costly overruns.[19,20] The implementation of IAEA safeguards measures to detect the misuse, diversion, or undeclared production of special nuclear material (SNM)[21] would fall within the context of proliferation resistance measures. The use of hot cells to provide passive barriers in terms of SNM accessibility would fall under physical protection measures. Currently, the HRS approach is focused on diversion of SNM from a legally declared pyroprocessing facility.

For the advanced fuel cycle, the composition of SNM is different in both chemical and physical form than in contemporary, PUREX processing facilities. Therefore, new approaches for safeguardability are needed. The proposed HRS approach is intended to be flexible and adaptable as future research informs new areas for refinement. In this paper, the fundamental principles for a safeguards-motivated systems assessment is proposed and qualitatively discussed.

Because there are no commercial pyroprocessing facilities currently under construction or design, the proposed HRS approach is largely theoretical currently. The intent of this paper and Borrelli (2014)[5] is to establish high-level principles for safeguardability that can initially serve as a guide in the formation of a design strategy. Then, these principles will be refined and adapted to a more practical end as modeling studies are initiated. A further intent to the development of the methodology is that materials in the advanced fuel cycle will be in a different chemical and physical form than in the contemporary fuel cycle. Therefore, it is proposed that current practices will require modification, the manner of which is to be the subject of the research into safeguardability within this context.

Scope

In this paper, the major points with respect to the functional components to the facility design are first summarized in order to provide context for the present discussion.[5] This includes brief overview of pyroprocessing and the SBD concept. The risk-informed, performance-based framework to assess safeguardability is the main focus of the paper and subsequently discussed. Practical difficulties to this approach and direction for future work are offered in conclusion.

Background

Pyroprocessing

Pyroprocessing is an electrochemical process by which a metal fuel alloy of uranium and TRU are fabricated from used uranium oxide fuel at high temperature. Materials are pyrophoric and an inert atmosphere is required. All major processes are conducted in hot cells that serve as biological shielding due to radiation levels. There are five main components to pyroprocessing: voloxidation, electroreduction, electrorefining, electrowinning, and metal fuel fabrication. A schematic diagram for the material flowsheet is given in Figure 1.[5]

Voloxidation converts UO_2 to U_3O_8 powder. Oxide powder is then converted to metal by electroreduction. Electrorefining and electrowinning are key processing steps in this system with respect to safeguards. Electrorefining separates uranium from TRU and the remaining fission products by dissolving the electroreduced metal anodically in a eutectic salt, and, in electrowinning, TRU, along with trace amounts of uranium and lanthanides, are separated from the eutectic salt and collected on a liquid cadmium cathode. For the concept shown by Figure 1, metal fuel is fabricated by injection casting. Metal feedstock is first melted by an induction furnace, and a vacuum is induced to inject the molten alloy into quartz molds. The molds are then sheared to obtain the metal slugs. For this fuel concept, the metal fuel product contains U, TRU, rare earth (RE) fission products, and zirconium, and exhibits a composition of 65U-20TRU-5RE-10Zr by weight percent.

Safeguardability Overview

Safeguardability[3,5] integrates proliferation resistance and physical protection measures with safety and physical security as part of a facility design strategy. This approach was based on the lessons learned from previous reprocessing facility design and construction.[19,20] Within this, the concept of safeguards-by-design (SBD)[14-18] is applied. SBD refers to the implementation of IAEA safeguards to detect the misuse, diversion, or undeclared production of special nuclear material (SNM)[21] during the design phase. Such efforts would fall within the context of proliferation resistance measures. These are further classified by intrinsic measures, including material properties and engineering design features, and extrinsic controls, such as treaties.[3,15-17,24-28] The goal of physical protection systems are to prevent or deter theft of SNM during the use, storage, and transport or sabotage of nuclear facilities by subnational entities or other non-host state adversaries.[3,19] Additionally, estab-

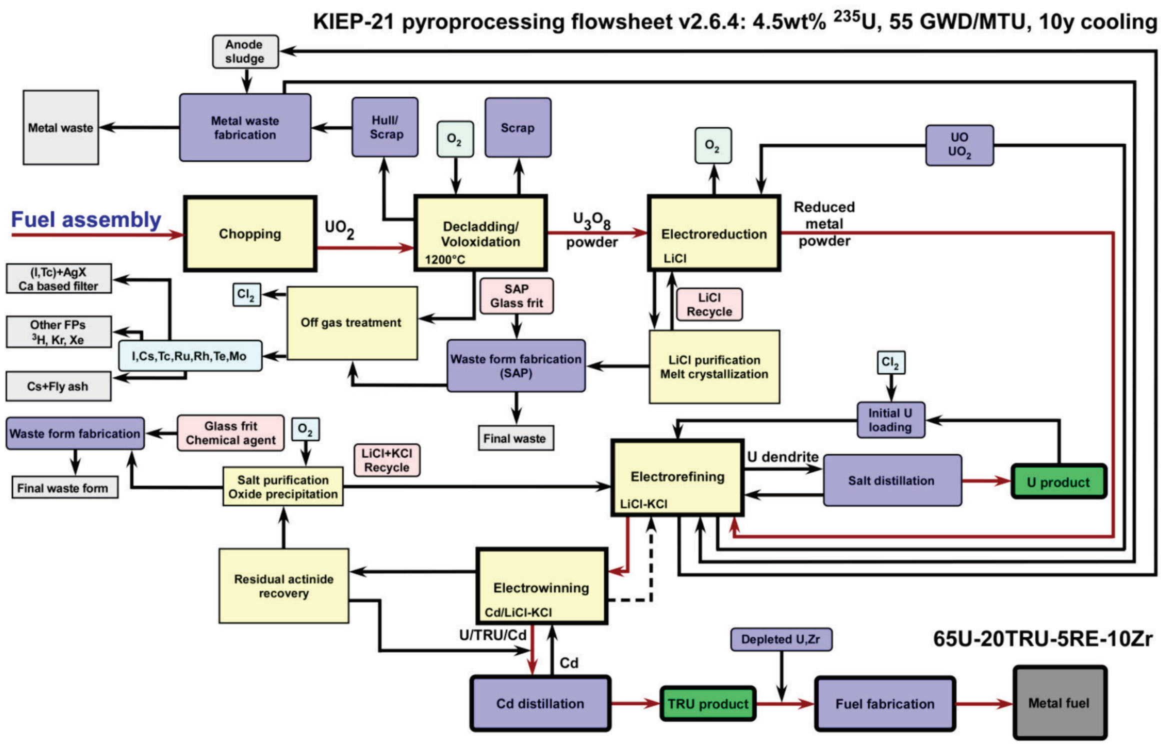


Figure 1. Pyroprocessing treats used UO_2 ceramic fuel and fabricates a metal fuel alloy comprised of uranium, TRU, rare earth (RE) fission products, and zirconium. The used fuel composition from a typical PWR (e.g., OPR-1000) in ROK exhibits a composition of 4.5 percent ^{235}U enrichment with 55 GWD/MTU burnup and a ten-year cooling time. There are five main subsystems: voloxidation, electroreduction, electrorefining, electrowinning/cadmium distillation, and metal fuel fabrication. These processes are highlighted with thick borders and primary material flow is shown by the red arrows. Treatment and recycle of eutectic salts from the electroreduction and electrorefining processes is also a major design consideration in the KIEP-21 concept. The metal alloy fabricated by pyroprocessing exhibits a weight percent of 65U-20TRU-5RE-10Zr. This material flowsheet is for exposition purposes should be considered notional only.

lishing passive barriers as part of the facility design in terms of impediments to SNM accessibility would fall under physical protection measures. Safeguardability can potentially be achieved through holistic, risk-informed methodologies that examine the relative performance of the full system.[14-18,23] There are no current, formalized standards on either the national or international level for safeguardability.

Achieving safeguardability is highly dependent on a robust state regulatory infrastructure. Non-nuclear weapons states (NNWS) provide notification to IAEA for any facility used to handle or produce SNM through the Comprehensive Safeguards Agreement (CSA) and the Additional Protocol (AP).[21,25,29-31] The state regulatory infrastructure also provides extrinsic controls over facility technical specifications, quality assurance, safety and physical security, and international and domestic safeguards.[14-18] It is important then to identify common goals of the national regulator, the state-based systems of accounting and control (SSAC) and material control and accountancy (MC&A) with IAEA early in system design phases. This is not to imply that IAEA will assume a legal role regarding state regulations or systems designs; however, with the development of advanced nuclear energy systems, the legal role of IAEA will evolve as studies into safeguardability methodologies mature.

Summary of the HRS Functional Components to Facility Design

The HRS approach is a methodology to deter misuse or diversion of SNM for an advanced fuel cycle by integrating proliferation resistance and physical protection measures with safety and security concerns. Initially, a commercial pyroprocessing facility is used as an example system. First, a set of functional components was proposed as part of a facility design strategy.[5] These are informed by contemporary best practices; however, because SNM is processed in different chemical and physical form than in existing reprocessing facilities, their application may also be different or require refinement as the HRS methodology matures. Therefore, these functional components are intended to provide an initial basis for a conceptual design strategy. Additionally, due to the different forms of SNM in pyroprocessing, the manner in which processing and maintenance cells are designed and configured will affect both operational goals and safeguardability. HRS is being developed in order to establish sensible design options that will provide a very low rate for false alarms and false positives and high probability of detection of diversion of material.[21,32,33]

Because SNM is treated by batch-processing in the pyroprocessing system, the extended containment and surveillance (ECS) concept is applied in the HRS methodology[34,35] This features the use of containment and surveillance (C/S) measures as the primary means to monitor "credible penetrations," defined as the technically feasible ways in which SNM could be transferred through a material balance area (MBA) by directing more monitoring efforts at key measurement points (KMPs). The function of nuclear materials accounting (NMA) then is to provide defense-in-depth and to reestablish continuity of knowledge (COK) if an anomaly in the C/S monitoring required IAEA inspection. A key feature of ECS is to design the facility such that personnel access to sensitive areas is very limited. This is potentially attractive for a facility where hot cells are utilized in that access to them during normal operations will be restricted.

The functional components established for the HRS approach as part of a design strategy for the facility are:[5] separation of process and maintenance activities, monitoring of material transfers, secure shutdown, and cell cleaning. Processing equipment should be very limited in functionality, and, conversely, for maintenance requirements, it is important to have equipment with significant flexibility. Separation of maintenance into a dedicated secure cell then can limit diversion pathways. Material transfers should be fully monitored and the data should be accessible to the IAEA. A secure shutdown mode would be analogous to a reactor scram. If the safeguards system departs from specified operating limits, then this shutdown mode would immobilize all materials and de-energize all transfer equipment. In order for this to be a practical component in a safeguardability methodology, first, operating limits for the facility, in terms of safety and security, as well as safeguards, where initiating events due to a random failure may result in an increase in diversion risk, would need to be established. This is partially the goal of the risk-informed approach under HRS. These operating limits would also be required in order for the operator to obtain a license for the facility as well. The shutdown is therefore engaged in order to collect and inventory any dispersed special nuclear material. Subsequent re-start of the facility would then require IAEA inspection. While it is currently not realistic to have the IAEA legally dictate facility operations, results of the inspection could serve primarily as a recommendation or advice for the operator as well as an opportunity for inventory verification.

Finally, cell cleaning would be required in order to provide a high level of assurance that any material held up in equipment cannot be removed from the hot cell without detection. These materials held up in the equipment due to normal or inadvertent causes from the process cell must be reliably monitored, quantified, and removed. Additional considerations then would include how facility layout can be practically devised based on these components. It should also be stressed that no safeguards approach will be comprehensive or robust without also including extrinsic controls.

Integration With Safety and Security Under HRS

A Risk-informed Approach for Advanced Reactor Systems

Safety

The HRS approach is fundamentally based on the integration of safeguards with safety and physical security for the pyroprocessing facility. This can be potentially achieved by considering the safety licensing approach for advanced reactor systems that is based on a technology-neutral, performance-based, and risk-informed framework.[3,36-42] This is based on three main principles: protection of public health and safety, continuing implementation of defense-in-depth practices, and development of quantitative guidelines for safety. These quantitative guidelines establish acceptable risks such that all the varied reactor designs can be evaluated with the same criteria.

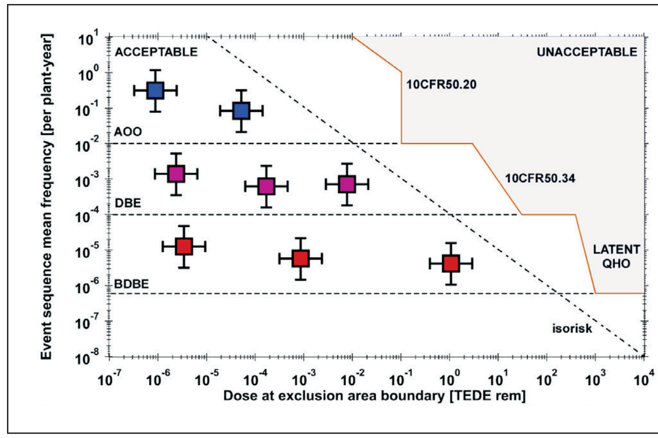
The objective then is to establish a licensing basis envelope (LBE) for a given facility by identifying initiating events that could lead to a range of accidents and designing the facility such that these are mitigated. The LBE must be comprehensive and include off-normal events that are frequent, infrequent, and rare, as well as events occurring during normal operation that could lead to an accident. These will include random failures such as systems, structures, and components (SSC), malfunctions leading to loss of power, natural phenomena related to weather, earthquakes, and tornadoes, or fire both internally and externally generated, human errors of any type that are unintentional, and malicious human actions such as sabotage or terrorism from insiders, outsiders, or a combination thereof.[43] All of these events can lead to accidents or loss of material accountability or material control. Initiating events to be included in the LBE must ensure that the design of the facility satisfies the design criteria for such events with margin and uncertainties, as well as additional defense-in-depth requirements.[36-39,41]

Facility safety risk is then determined by establishing frequencies for the initiating events that lead to accidents and the subsequent system response. For a reactor facility, the consequence is dose at the exclusion area boundary.[38,39] Facility safety is analyzed using probabilistic risk analysis (PRA).[36-39,41,42,44] There are extensive, widely established techniques used to formulate a PRA, and these are also acceptable for approaches to advanced reactor safety and physical security.[45] PRA tools include both quantitative and qualitative fault and event trees, and complementary bottom-up approaches such as failure, modes, and effects analysis (FMEA) for studying failure modes and related uncertainties, or hazard and operability analysis (HAZOP) for events leading to multiple consequences.[42,46-49] A full discussion regarding the theory and use of PRA is beyond the scope of this paper. In terms of HRS, PRA is intended to be used as part of this risk-informed approach. The effectiveness of which is the subject of initial study to this end.

PRA is used to produce the "Farmer's curve," where acceptable limits for potential accidents and resultant consequences are established (see Figure 2).[50] The safety goals for facility design are to guarantee extremely low consequences for frequent events and extremely low frequencies for severe events. The goal of using the PRA for facility safety is to assemble a set of bounding events and related accident sequences and demonstrate that acceptable risk, adequate defense-in-depth, and safety margin for public health and safety can be achieved for the proposed LBE.

Initiating events are categorized as follows, from low frequency and then increasing: anticipated operational occurrences (AOOs) occurring during the typical lifetime of the facility, design basis events (DBEs) occurring over the lifetime of a population of facilities, and beyond design basis events (BDBEs) that are not likely to occur over the lifetime of the population. The AOOs exhibit mean frequencies of greater than

Figure 2. This notional Farmer's curve for reactor safety shows the classes of different initiating events. (Click to view larger version.)



10^{-2} per facility-year, mean frequencies for DBEs fall between 10^{-2} and 10^{-4} per facility-year, and BDBEs with mean frequencies between 10^{-4} and 5×10^{-7} per facility-year.[37] Events below a frequency of 5×10^{-7} are considered extremely rare and not included in the safety analyses. For reactor systems, fatality risk is based on quantitative health objectives (QHOs).[37,39] These QHOs provide quantitative criteria that are used to establish acceptable levels of risk for each facility:[51] (1) "The risk to an average individual in the vicinity of a nuclear power plant of prompt fatalities that might result from reactor accidents should not exceed one-tenth of one percent (0.1 percent) of the sum of prompt fatality risks resulting from other accidents to which members of the U.S. population are generally exposed;" and (2) "The risk to the population in the area of nuclear power plant of cancer fatalities that might result from nuclear power plant operation should not exceed one-tenth of one percent (0.1 percent) of the sum of cancer fatality risks resulting from all other causes." Therefore, QHOs are expressed as individual risk of a latent fatality (2×10^{-6} per year) and an early fatality (5×10^{-7} per year) from the exclusion area boundary of the facility.[37,39] The Farmer's curve should demonstrate that the total frequency of all initiating events should satisfy both conditions.

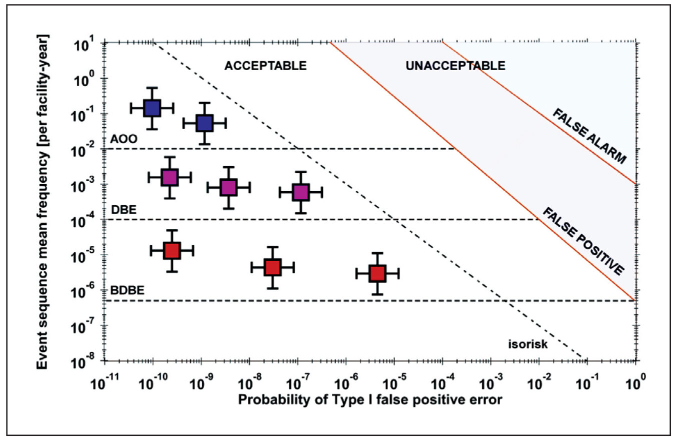
The initiating events included in the LBE must be shown to meet the criteria of the Farmer's curve in that the frequencies and consequences of all sequences have to lie in the acceptable region based on the relevant regulations and QHOs.[39] A notional representation for a typical Farmer's curve with these frequencies and associated acceptable risks is shown in Figure 2 for reactor safety that includes the relevant regulations for acceptable risk.[43] For the LBE for any reactor facility, when constructing the Farmer's curve typical of Figure 2, AOOs will have the highest frequency but should exhibit the lowest dose. The remaining classes are decreasing in frequency, but dose releases are higher, as shown. Risk acceptability is determined by U.S. Nuclear Regulatory Commission (NRC) regulations. 10CFR50 Appendix I provides regulations for doses that are ALARA from normal operation of nuclear power plants.[52]

Security

Similarly, the risk-informed approach can be applied to security to be evaluated integral with facility design, safety, and preparedness.[39,53-55] Security goals are to provide enhanced safety margin and to employ inherent, passive, or other innovative means to accomplish safety and security functions such that security is integrated with safety into facility design and consistent with safety goals for public health protection and utilizing defense-in-depth.[39,54] These would then be incorporated into regulatory review of the facility. To this end, set of design basis threats (DBTs) are established as well as a set of events that will fall outside the DBTs. Performance assessment of the security systems will entail threat and target identification and related consequences, in a similar manner to safety, in that PRA could be extended to model malevolent initiating events related to security. Frequencies for the threats will be established for the assessment. Unlike safety, however, these frequencies are dependent on unknown information to the defender, based solely on adversary action; therefore, conditional risk is critical in the proposed security performance standards.[39,53] A security-related scenario then can be represented as a timeline of possible actions by the adversary for a defined goal, where PRA can be utilized to assess the actions.[55]

The DBTs should be established for threats over the life cycle of the facility. Such threats include insider attack, armed intrusion, stand-off attacks, cyber attacks, and theft, diversion, or sabotage of SNM.[39] Recommendations for advanced systems then is to develop security performance standards that are risk-informed and performance-based, while mitigating risk common to safety by appropriate facility design.[39] Similar to safety, frequency of the threats are quantified with appropriate levels of mitigating actions to the security standards subsequently formulated. This will involve similar probabilistic analyses as that of safety, in terms of threats rather than random failures of operational events. This is clearly a difficult approach, with each threat accompanied by uncertainties due to unknown adversary information. These are more applicable therefore as conditional upon the initiating threat and then used in an integrated decision-making process that considers all factors in safety and security.[39] The facility design must allow for multiple defense pathways for any particular security-based initiating event. This is more readily achieved by considering these actions during the design phase of the facility. Therefore, overall safety and security can take advantage of defense-in-depth by functional components to the design.

Figure 3. This notional Farmer's curve is proposed for the safeguards system, similar in principle to the, risk informed approach established for advanced reactor systems safety. (Click to view larger version.)



Qualitative Discussion of the Approach Applicable to Pyroprocessing

Establishing such an approach to the commercial pyroprocessing system is challenging initially due to the lack of practical operational experience. However, a qualitative discussion is useful for future direction. At the outset, this approach should rely heavily on engineering judgment, and, therefore, should include a wide range of experts and collaboration to establish a robust knowledge base.

Potential Application to the Pyroprocessing Facility

The risk-informed approach for reactor systems is rigorous and robust. However, the licensing approach for advanced reactors utilizes the current regulations for light-water reactors for general guidelines, and, practically, when assembling an LBE for any of these systems, at the outset, considerable engineering judgment will be required, due to a lack of operational history and data cohorts. This is especially the case for the pyroprocessing facility. An additional complication is that much of the current laboratory-scale experimental results with regard to all the complicated subsystems in pyroprocessing cannot be readily scaled to the commercial level. There are clear similarities in the challenges to safety approaches for the advanced reactor systems and for the safeguards of the commercial pyroprocessing facility. It is proposed that this risk-informed methodology can exhibit similar utility to the safeguards system as it has been shown for the advanced reactor systems. Requirements for both defense-in-depth and physical protection can be determined in conjunction with the safeguards system analysis, as well as identifying systems, structures and components common to all these areas in an effort to avoid designs that detract from overall efficiency of safeguards, safety, and physical security systems, prior to construction of the facility.

In terms of safeguards assessment, the related metrics are the false positive or false alarm (Type I error) and non-detection of diversion, if a diversion event actually occurred (Type II error).[21] An event leading to a false alarm or false positive could arise from random failures and malfunctions, natural phenomena, loss of power, fire, or human error. These events could occur during normal operation or physical security events. In a similar manner to the risk-informed approach for reactor safety, for the safeguards system the initiating event frequencies could be related to the probability of the Type I error. For a false alarm, an IAEA inspection would be required for full resolution, costing time and resources. Additionally, for a false positive, an IAEA inspection would not be able to confirm the absence of diversion or misuse, or incorrectly confirm that diversion or misuse has occurred. Therefore, the implications to this could be devastating for the state, politically, and, possibly, economically. All stakeholders in a pyroprocessing facility, then, would have strong desires in designing the facility to achieve the lowest rates of Type I error. The significance of the Type I error within the context of the HRS methodology is that it can be a way to integrate safety, safeguards, and security for a safeguards-motivated systems assessment.

This is not to discount the importance of the Type II error. However, the Type II error does not result from the initiating events described above but rather arises from a strategic decision by the state to initiate action to divert SNM. Deterrence is this way could presumably be achieved even with a relatively large magnitude for the Type II error. With a non-detection probability of 0.10, for example, the state would have to initiate ten diversion attempts in order to for one of them to be successful. Presumably, any state would be deterred from such action due to the severe implications if the attempt were detected. Therefore, currently, the Type II error is not considered. Because there is the mathematical relationship between the two metrics the Type I error will be studied first as part of the risk-informed approach, and then the associated Type II error will be subsequently considered in relation.

To this end, a notional Farmer's curve is shown in Figure 3 for the safeguards system that is similar in principle to the risk-informed approach established for reactor safety. Frequencies can be determined for initiating events, and the consequence proposed here is the probability of a false positive error. Risk acceptability would have to be determined by the regulator and be legally binding. Frequencies then can be proposed for the AOOs, DBEs, and BDBEs that lead to the safeguards anomaly. Currently, this will be difficult due to the lack of operational experience. However, it is expected that the events that constitute each category could be formulated further once a more rigorous analysis is conducted based on developing experiences. For safeguards-related AOOs, which are expected to occur with relative frequency, the probability of false positive anomalies should be kept at very low levels. Infrequent events should also exhibit sufficiently low probabilities for false positives as well, so as to minimize overall risk. Acceptable risk for the false positive in Figure 3 is nominally established at the level of 5×10^{-7}, based on the QHO quantitative goals, and the false alarm at 10^{-3}, consistent in the licensing approach for triggering EPA Protective Action Guidelines.[39] These are based on the existing studies for reactor safety; clearly, analyzing safeguards risk for a pyroprocessing facility will be quite different. The use of 5×10^{-7} is a starting point for discussion. Acceptable risk criteria must be determined by the regulatory authority. In principle, Figures 2 and 3 are presented to show that an approach to safeguards assessment can be developed based on this accepted framework. Therefore, risk from safeguards, safety, and physical security can be identified collectively and the design of the pyroprocessing facility can be subsequently modified to optimize the system based on these commonalities in risk in order to detect or divert a diversion attempt. The goal is to formulate facility design options based on the assessment that will render diversion strategies technically difficult, time-consuming, and costly, as well as affording a high detection probability. These potential diversion strategies would all require rigorous analysis in order to determine if the facility design can achieve these objectives.

Applying PRA principles for a Farmer's curve-type approach to safeguards has similarly been proposed for the sodium cooled advanced reactor design, where the frequency is the Type II error, and the consequence is the fraction of a significant quantity (SQ) diverted.[41] This is clearly a different application of the risk-informed methodology than what is discussed here, but nonetheless supports the use of the approach to safeguardability.

Examples of Initiating Events Specific to Pyroprocessing Operation

The electrorefining and fuel fabrication systems have been used as examples for discussion of the HRS approach.[5] Returning to these, several initiating events are apparent that would lend to a PRA-type analysis for safeguards. For either of the systems, during normal operations, routine maintenance activities will occur. The difficulty to detect diversion will be greatly increased when the hot cell is opened and entered in order to remove and replace equipment. This will happen with regularity and should be classified as AOOs. For example, in the electrorefining equipment, the graphite cathodes will have to be replaced, presumably after a full campaign, or after a certain throughput has been achieved. The anode basket will need similar replacement. Salt recycle is a key feature in the electrorefining process; therefore, there may be regular periods of shutdown while sufficient quantities of salt are cleaned and transferred. Or, if the salt recycle procedures are intended to be a continuous process, then issues with salt loading may be classified as a less frequent event (DBEs). These also could include problems with the equipment used to scrape U metal from the cathode. Other operational failures include the heating equipment or a malfunction in UCl_3 loading. Events such as a loss of the Ar atmosphere or failure of vacuum pumping are severe and could lead to fire and would be classified as BDBE-type events.

Similar discussion can be brought forth for the fuel fabrication process. AOOs could include regular replacement of the graphite crucible due to cracking from the high heat. The quartz molds used for slug casting of the molten alloy may also crack when loading into the melter/caster equipment. Uneven heating of the alloy may not be complete and homogenous, and therefore may need to be restarted. This would temporarily interrupt processing. It is not clear, however, as to the frequency of a heating failure. Presumably, this should not occur often and may be classified as a DBE. Other less frequent events then could include malfunctions with the motor that drives the molds into the alloy. The molten alloy may not completely fill each of the molds, which then would require the process to be restarted. In this case, the molds may have to be broken to obtain remaining alloy to be returned to the melting/casting equipment. This will clearly be a lengthy process and should not occur frequently. The equipment used to trim and break the molds may also malfunction. Inspection of this equipment might be conducted during the expected times for routine maintenance. Therefore, the equipment could be replaced during normal shutdown maintenance periods without additionally affecting operation. Like the electrorefiner, the key BDBE would most likely be the loss of the Ar atmosphere. These examples demonstrate how events for consideration in a potential LBE can begin to be identified. This will eventually require detailed study of each process in the system.

Off-normal, Safety, Physical Protection and Security, and Other Considerations

Presumably, for off-normal events, such as loss of power, or an external fire, there is sufficient commonality with existing safety, physical protection, and security of nuclear facilities in order to formulate a reasonable LBE initially. Similar events, not specific to pyroprocessing activities, also could be applied from experiences at other facilities. For example, for natural phenomena, this would be predicated on climatological conditions of the host-state.

C/S reliability analysis for safeguards, for events such as camera, seal, or computer failure can also be drawn from efforts elsewhere, such as on-site used fuel storage monitoring. Additionally, mechanical reliability of the transfer gates for material transfers could also be analyzed based on similar systems. Risk of fire can draw from industry best practices in fire protection engineering. Further C/S systems design then would need to consider visibility and reliability in such conditions. In the event that a fire disables C/S equipment, then the accounting inventory would be needed to restore continuity of knowledge.

The key issue affecting safeguards for the pyroprocessing system would be events that require entry to the hot cell. There are many initiating events where this action would result. For all of them, opening and entering the cell carries the highest relative diversion risk for systems like the electrorefiner, in which TRU is or has been separated. Conversely, diversion risks are relatively low in the pyroprocessing facility in that during normal operation, all activities are occurring in the sealed hot cells. The cells will not be able to be entered at this time undetected with the proper monitoring systems and personnel controls. For most of the initiating events, for example, perhaps those that would be classified as DBEs or BDBEs that could occur during normal operation, the secure, shutdown mode should be initiated to cease all operational activities. Personnel would have to enter the hot cell to remove equipment, and clean the cell, posing a diversion risk. Strict procedures and monitoring must be in place in order to document when the cell is opened and who has access to enter. IAEA inspectors would need to be present and provide authorization to resume normal activity after such actions and to verify inventory is consistent with declared activity.

Because the shutdown mode necessitates such intensive action, a rigorous analysis would need to establish which events require immediate action and which could be left until normal maintenance is conducted. The loss of a single quartz mold in the fuel casting equipment will not affect overall throughput to a great extent, and therefore immediate shutdown may not be required. For these events, defense-in-depth will play a strong role. The cell could store spare molds and replace the defective mold once the injection process is complete. This is not entirely unreasonable since the molds are broken after every injection for trimming to obtain the alloy slugs, and therefore, full shutdown of the facility to enter the cell and replace molds after each batch is processed is not operationally practical. Presumably, there would be a large supply, possibly determined by operational goals and material throughput with equipment to load fresh molds into the melter/caster. Similarly, clean salt probably would be prepared outside of the electrorefining hot cell, since it does not initially contain SNM, and transferred into storage within the cell. Since the recycle and distillation of the salt will not be 100 percent efficient; there would be expected process losses. Available quantities of clean salt in the cell therefore may reduce the frequency of shutdown as well. Much of this also would be determined on operational goals of the facility and the subsequent physical layout. Incorporating best practices when experience becomes available should be included for this approach. Lessons learned for security and safety from other nuclear facilities that use hot cells to some extent, such as a PUREX or MOX processing facility also may prove useful. Malevolent initiating events related to physical security could also result in a safeguards anomaly and require shutdown. Threats for malevolent acts against nuclear facilities share common adversary strategies and may be applied to the pyroprocessing facility.

The safeguards system will share common areas of risk with that of safety and physical security. This methodology will be initially challenging to practically implement, most likely due to additional uncertainties resulting from the lack of operation experience. However, this risk-informed approach offers substantial benefits to demonstrating the safeguardability of the commercial pyroprocessing facility.

Safeguards Performance Assessment

Safeguards systems assessment can be achieved by utilizing a pathways-based approach, consistent with the risk-informed methodology.[3,40] The main objectives of the safeguards system are to make potential diversion strategies technically difficult, time-consuming, and costly. The goal of a systems assessment for the pyroprocessing facility then is to model the frequency of initiating events in a proposed LBE, incorporate additional diversion strategies that challenge physical protection and security, and then evaluate the system response to them in terms of the false positive anomaly. This would involve determining whether the material unaccounted for (MUF) from a material balance area (MBA) over a period of time provides evidence as to whether a specified diversion strategy has occurred. Establishment of MBAs, in turn, will be greatly affected by the facility layout and therefore an extensive assessment of many facility layouts as part of the conceptual design process is necessary in order to optimize operational goals with safety, safeguards, and security considerations. Initial systems assessments may exhibit considerable uncertainties; it may be instructive for early assessment to be more qualitative in nature, relying on expert judgment.[27] This may assist in either including or eliminating initiating events in the LBE or re-classifying the events from AOOs to DBEs, BDBEs, or otherwise. Other nuclear systems could serve as analogues; for example, fuel fabrication in a MOX facility could be utilized as a base for reliability of common equipment, such as manipulators or detectors, as well as other C/S monitoring equipment. Approaching the systems assessment in this manner will allow for iterative design optimization of the facility and further refinement of the functional components. This will also provide a measure of the safeguardability of system and facility design in terms of cost and operational objectives. As conceptual facility design matures, a more rigorous analysis then will be applied for further assessment and reduction of uncertainties.

Regulatory Considerations

The utility of the HRS approach is predicated on a strong state regulatory infrastructure. Practically, for the operator of a potential pyroprocessing facility, the economics will be a driving factor underscoring success. Therefore, cooperation with the regulatory body is important. This will also be the case with implementation of safeguards, as an IAEA inspection will be required after any shutdown or major safeguards anomaly. Furthermore, legally binding penalties for safeguards, similar to that of safety will be necessary. This is not currently the case. The IAEA must possess additional legal authority to review and approve the design, technical specifications, license application, and any license amendments for those elements that affect safeguards performance, equivalent to the legal authority the national regulatory body holds for those that relate to safety and physical security. This could be possibly achieved through amendment of the Comprehensive Safeguards Agreement or Additional Protocol with the IAEA based on eventual formalized safeguards goals for these facilities.

The initial design of a facility will require comprehensive interaction with the IAEA, national regulatory body, and the operator. Achieving a high-level of transparency amongst all of these stakeholders is critical in the identification of common goals pertaining to safeguards, safety, and physical security. This must continue throughout licensing, construction, and operation of the facility. For example, during construction and maintenance, nuclear facility licenses also require the implementation of an effective quality assurance (QA) program to assure that the facility is constructed and maintained consistent with its original design. These requirements overlap IAEA requirements for design information verification (DIV). Close integration of QA and DIV would be recommended during facility design. Transparency also will involve the transmission of relevant safeguards-related data to the IAEA, in terms of signals related to commercial operating activities, as well as for confirmation of SNM transfers, in order to be consistent with declared facility operation. However, there will be additional burden placed upon the IAEA to evaluate new facilities due to a lack of historical data and experience. Efforts to standardize facility designs would be beneficial to this end and reduce the inspection workload.

Challenges to Practical Implementation

Formulation of a rigorous safeguards approach to the commercial pyroprocessing system is currently constrained, primarily due to the lack of any operational data cohort and problems with scaling throughput based solely on experimental data from the laboratory scale to the commercial scale. Currently, therefore, studies of facility layout are useful for discussion and directing study but limited. Extensive engineering judgment would be needed to shape further study toward a more practical endpoint. Utilization of experience for similar nuclear materials processing is similarly limited, as pyroprocessing is a batch system for fabrication of a metal product; contemporary nuclear fuel commercial processing, involves continuous, aqueous processes for a ceramic product. Having a rigorous theoretical framework in place, with well-established, systematic modeling tools for safeguards assessment is a vitally important initial phase of this systems assessment.

Modeling of human action will also be difficult. While many adversarial human actions that challenge physical security will be common to both pyroprocessing and other nuclear facilities, pyroprocessing is unique in that all sensitive processes will take place in hot cells. Therefore, the primary goal for an adversary would be obtaining entry to the hot cell. Even if entry could be gained, commercial size batches exhibit significant radiation levels due to decay heat. This could make handling them for extended time periods prohibitive. Initial efforts to this end will also require expert judgment and contain a high degree of uncertainty. These events are not random in nature and will pose additional complexity. By maintaining a systematic approach in this way, and recognizing where uncertainties may arise, this should lend to useful insight into system design for both security and safeguards.

Because new legally binding measures will be needed, a new relationship with the IAEA and the state must be developed. This will require additional amendments to existing safeguards agreements in conjunction with the new regulations needed for the safeguards systems. There is currently not a set goal for the false positive anomaly, and without operational experience, this is difficult to formulate. In a way, this is a recursive problem, in that legally binding measures require a standard upon which to base the regulation, but the standard cannot be set without practical experience. The state that takes the lead to develop the safeguards system for such a facility in this way, could potentially serve as a model for others to follow. Therefore, implications of this undertaking could be more far reaching than initially conceived. This will require extensive transparency with the IAEA and considerable efforts throughout all phases of design and will place the state under high scrutiny in the international community.

Summary Remarks and Future Directions

The transition to a closed fuel cycle and deployment of advanced reactor systems will require new approaches to safeguardability. To that end, a high-reliability safeguards (HRS) approach has been proposed for potentially achieving safeguardability of remotely handled, batch processing materials fabrication facilities. An example pyroprocessing system was utilized for discussion. This approach applies the safeguards-by-design (SBD) concept to integrate safeguards, safety, and physical security. First, adaptable, functional design components to the system design were proposed. In this paper, methodology was extended by introducing a risk-informed framework to integrate safeguards with safety and physical security in a way such that safeguards anomalies can be quantified in terms of risk to the facility.

A licensing envelope can be developed for initiating events that could lead to a safeguards anomaly, encompassing low-frequency normal, operational occurrences to higher-frequency off-normal events. The frequencies of these events can be modeled by a PRA-type analysis, where, for these initiating events, the probability of the false positive or false alarm error is the consequence. A very low probability for false positive errors will be required for the commercial facility. This approach should offer a framework by which to identify commonalities in risk for safety, safeguards, and physical security, as well as offer insight at the conceptual design phase. The acceptability of these risks, however, while being informed by this approach, will be determined by the regulatory body and formalized IAEA safeguards goals. These should be legally binding similar to safety regulations and will require amendments to existing international safeguards agreements. Safeguardability for these facilities can only be achieved in conjunction with these intrinsic design efforts and extrinsic controls.

Future directions may be most useful by first identifying important subsystems with respect to safeguards and qualitatively analyzing operational states and initiating events leading to potential false positive anomalies. Frequency analysis at this time should apply existing analogues and rely considerably on engineering judgments. It may be more useful first to conduct sensitivity analyses of potential accident frequencies and malfunctions to the Type I error. These results then can be utilized to refine the initiating event classifications. This would require further quantitative modeling of material throughput for the subsystems. The utility of the HRS methodology then can be assessed for more practical and complex scenarios in order to evaluate the safeguardability of remotely handled nuclear facilities.

Acknowledgements

This paper was supported by funding from the Korean Atomic Energy Research Institute (KAERI) in collaboration with the University of California-Berkeley, Department of Nuclear Engineering (UCBNE).

References

1. U.S. Department of Energy and the Generation IV International Forum. 2002. A Technology Roadmap for Generation IV Nuclear Systems: Ten Nations Preparing Today for Tomorrow's Energy Needs, *GIF-002-00*.
2. Peters, M. T. 2009. *Testimony to United States House of Representatives, Committee on Science and Technology*, 17 June 2009.
3. The Proliferation Resistance and Physical Protection Evaluation Methodology Expert Group of the Generation IV International Forum. 2011. Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems, Revision 6, *GIF/PRPPWG/2011/003*.
4. Kim, H-D., H. S. Shin, and S. K. Ahn. 2010. Status and Prospect of Safeguards by Design for the Pyroprocessing Facility, *IAEA-CN-184/71*.
5. Borrelli, R. A. 2014. The High Reliability Safeguards Approach for Safeguardability of Remotely-Handled Nuclear Facilities: 1. Functional Components to System Design, *Journal of Nuclear Materials Management,* Volume 42, No. 3.
6. Yoon, J., and J. Ahn. 2010. A Systems Assessment for the Korean Advanced Nuclear Fuel Cycle Concept from the Perspective of Radiological Impact, *Nuclear Engineering and Technology* 42, 17.
7. Yoon, J., and J. Ahn. 2011. Performance Assessment for Korean Concept of Geological Disposal, *Proceedings of the International Conference on High-Level Radioactive Waste Management*.
8. Hwang, Y., M. S. Jeong, and S. W. Park. 2007. Current Status on the Nuclear Back-End Fuel Cycle R&D in Korea, *Progress in Nuclear Energy* 49, 463.
9. Lee, K. J. 2008. Spent Fuel Management with Pyroprocessing: The Advantages of the Pyroprocessing Option from the Perspective of Waste Management, *KAERI Nuclearancy* 1, 8.
10. Korean Ministry of Knowledge Economy. 2008. National Energy Basic Plan 2008, *Press Release*, 28 August 2008.

11. Ko, W. I., and E-H. Kwon. 2009. Implications of the New National Energy Basic Plan for Nuclear Waste Management in Korea, *Energy Policy* 37, 3484.
12. McGoldrick, F. 2009. New U.S.-ROK Peaceful Nuclear Cooperation Agreement: A Precedent for a New Global Nuclear Architecture, *Center for U.S.-Korea Policy, A Project of the Asia Foundation*.
13. Park, S-W., M. A. Pomper, and L. Scheinman. 2010. The Domestic and International Politics of Spent Nuclear Fuel in South Korea: Are We Approaching Meltdown? *Korea Economic Institute Academic Paper Series* 5, 1.
14. Bean, R. S., T. A. Bjornard, and D. J. Hebditch. 2009. Safeguards-by-Design: An Element of 3S Integration, *IAEA-CN-166/067*.
15. Bjornard, T., R. Bari, D. Hebditch, P. Peterson, and M. Schanfein. 2009. Improving the Safeguardability of Nuclear Facilities, *Journal of Nuclear Materials Management,* Volume 37, No. 4.
16. Bjornard, T. A., J. Alexander, R. Bean, P. C. Durst, B. Castle, S. DeMuth, M. Ehinger, M. Golay, K. Hase, D. Hebditch, J. Hockert, B. Meppen, J. Morgan, and J. Phillips. 2009. Institutionalizing Safeguards by Design: High-Level Framework, *INL/EXT-08-14777*.
17. Bjornard, T., R. Bean, Phillip C. Durst, J. Hockert, and J. Morgan. 2010. Implementing Safeguards-by-Design, *INL/EXT-09-17085*.
18. Hebditch, D. J., S. J. Third, J. P. Martin, and M. Wise. 2010. International Development of Safeguards and Security by Design of Nuclear Facilities and Processes, *Proceedings of the Waste Management Symposium 2010, WM2010*.
19. Ehinger, M. H., and S. J. Johnson. 2009. Lessons Learned in International Safeguards - Implementation of Safeguards at the Rokkasho Reprocessing Plant, *ORNL/TM-2010/23*.
20. Johnson, S. J., and M. H. Ehinger. 2010. Designing and Operating for Safeguards: Lessons Learned from the Rokkasho Reprocessing Plant (RRP), *PNNL-19626*.
21. International Atomic Energy Agency. 2002. *IAEA Safeguards Glossary, International Nuclear Verification Series, No. 3*.
22. Korean Atomic Energy Research Institute. 2010. High-Level Waste Long-Term Management Technology Development/Development of a Korean Reference Disposal System (A-KRS) for the HLW from Advanced Fuel Cycles, *KAERI/RR-3100/2009.*
23. International Atomic Energy Agency. 2008. *20/20 Vision for the Future, Background Report by the Director General for the Commission of Eminent Persons*.
24. Feiveson, H.. 2001. The Search for Proliferation Resistant Nuclear Power, *Journal of the Federation of American Scientists* 54, 1.
25. Bragin V., J. Carlson, and R. Leslie. 2001. Integrated Safeguards: Status and Trends, *The Nonproliferation Review* 8, 102.
26. Bragin V., J. Carlson, R. Leslie, R. Schenkel, J. Magill, and K. Mayer. 2007. Proliferation Resistance and Safeguardability of Innovative Nuclear Fuel Cycles, *IAEA-SM-367/15/07*.
27. Pomeroy, G., R. Bari, E. Wonder, M. Zentner, E. Haas, T. Killeen, G. Cojazzi, and J. Whitlock. 2008. Approaches to Evaluation of Proliferation Resistance of Nuclear Energy Systems, *Proceedings of the 49th Institute of Nuclear Materials Management Annual Meeting*.
28. Sevini, F., G. Renda, and V. Sidlova. 2011. A Safeguardability Check-List for Safeguards-by-Design, *ESARDA Bulletin* 46, 79.
29. International Atomic Energy Agency. 1970. Treaty on the Non-Proliferation of Nuclear Weapons, *INFCIRC/140*.
30. International Atomic Energy Agency. 1972. The Structure and Content of Agreements Between the Agency and States Required in Connection with the Treaty on the Nonproliferation of Nuclear Weapons, *INFCIRC/153 (Corrected)*.

31. International Atomic Energy Agency. 1997. Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency for the Application of Safeguards, *INFCIRC/540 (Corrected)*.
32. Avenhaus, R. 1977. *Material Accountability: Theory, Verification, Applications*. New York: John Wiley & Sons.
33. Goldman, A. S., Richard R. Picard, and J. P. Shipley. 1982. Statistical Methods for Nuclear Materials Safeguards: An Overview, *Technometrics* 24, 267.
34. International Nuclear Fuel Cycle Evaluation. 1979. PIPEX-A Model of a Design Concept for Reprocessing Plants with Improved Containment and Surveillance Features, *INFCE/DEP./WG.4/64*.
35. Lovett, J. E. 1987. Nuclear Materials Safeguards for Reprocessing, *IAEA-STR-151/152*.
36. Delaney, M. J., G. E. Apostolakis, and M. J. Driscoll. 2005. Risk-Informed Design Guidance for Future Reactor Systems, *Nuclear Engineering and Design* 235, 1537.
37. Silady, F.. A. 2005. Licensing Approach for Modular HT-GRs, *Proceedings of the International Topical Meeting on Probabilistic Safety Assessment*, (*PSA'05*).
38. U.S. Nuclear Regulatory Commission. 2002. Guidance for Performance-Based Regulation, *NUREG/BR-0303*.
39. U.S. Nuclear Regulatory Commission. 2007. Feasibility Study for a Risk-Informed and Performance-Based Regulatory Structure for Future Plant Licensing, *NUREG-1860*.
40. The Proliferation Resistance and Physical Protection Evaluation Methodology Expert Group of the Generation IV International Forum. 2009. PR&PP Evaluation: ESFR Full System Case Study Final Report, *GIF/PRPPWG/2009/002*.
41. Apostolakis, G., M. Driscoll, M. Golay, A. Kadak, N. Todreas, T. Aldemir, R. Denning, and M. Lineberry. 2011. Investigation of Risk-Informed Methodologies to Improve Sodium-Cooled Fast Reactor Economics with Safety, and Nonproliferation Constraints, *Proceedings of the ANS 2011 International Topical Meeting on Probabilistic Safety Assessment and Analysis*.
42. Verma, A. K., A. Srividya, V. Gopika, and K. D. Rao. 2011. Risk-Informed Decision Making in Nuclear Power Plants, in: *Safety and Risk Modeling and its Applications, Part 3*, H. Pham, (ed.), 10.1007/978-0-85729-470-8_12.
43. Kastenberg, W. E. 2002. Development of Risk-Based and Technology-Independent Safety Criteria for Generation IV Systems, *DE-FC07-05ID14666*.
44. U.S. Nuclear Regulatory Commission. 1975. Reactor Safety Study: An Assessment of Accident Risks in U. S. Commercial Nuclear Power Plants, *WASH-1400, NUREG-75/014*.
45. Tong, J., J. Zhao, T. Liu, and D. Xue. 2011. Development of Probabilistic Safety Assessment with Respect to the First Demonstration Nuclear Power Plant of High Temperature Gas Cooled Reactor in China, *Nuclear Engineering and Design* 10.1016/j.nucengdes.2011.09.055.
46. Gabbar, H. A. 2010. Integrated Framework for Safety Control Design of Nuclear Power Plants 240, 3550.
47. Lee, J-S., V. Katta, E-K. Jee, and C. Raspotnig. 2010. Means-Ends and Whole-Part Traceability Analysis of Safety Requirements, *Journal of Systems and Software* 83, 1612.
48. Rossing, N. L., M. Lind, N. Jensen, and S. Jørgensen. 2010. A Goal Based Methodology for HAZOP Analysis, *Nuclear Safety and Simulation* 1, 134.
49. Guimarães, Ferreira, Antonio César, Celso Marcelo Franklin Lapa, and Maria de Lourdes Moreira. 2011. Fuzzy Methodology Applied to Probabilistic Safety Assessment for Digital System in Nuclear Power Plants, *Nuclear Engineering and Design* 241, 3967.
50. Farmer, F. R. 1967. Reactor Safety and Siting: A Proposed Risk Criterion, *Nuclear Safety* 8, 539.
51. U.S. Nuclear Regulatory Commission. 21 August 1986. Safety Goals for the Operation of Nuclear Power Plants, *Federal Register* 51, 30028.
52. U.S. Nuclear Regulatory Commission. 2012. Part 50: Domestic Licensing of Production and Utilization Facilities, *Code of Federal Regulations, 10CFR50*.
53. Garrick, B. J., J. E. Hall, M. Kilger, J. C. McDonald, T. O'Toole, P. S. Probst, E. Rindskopf Parker, R. Rosenthal, A. W. Trivelpiece, L. A. van Arsdale, and E. L. Zebroski. 2004. Confronting the Risks of Terrorism: Making the Right Decisions, *Reliability Engineering and System Safety* 86, 129.
54. U.S. Nuclear Regulatory Commission. 25 September 2007. Revision of Policy Statement on Regulation of Advanced Reactors, *SECY-07-0167*.
55. Smith, C., D. Schwieder, and T. Bjornard. 2011. Augmenting Probabilistic Risk Assessment with Malevolent Initiators, *Proceedings of the 14th International Mechanical Engineering Congress & Exposition, IMECE 2011*.

Safeguarding the Military Naval Nuclear Fuel Cycle

Sébastien Philippe
Nuclear Futures Laboratory, Department of Mechanical and Aerospace Engineering
Princeton University, Princeton, New Jersey USA

Abstract

In the safeguards agreements between non-nuclear-weapon-state members of the Nuclear Nonproliferation Treaty and the International Atomic Energy Agency, there is a possibility for non-nuclear weapon states, acting with the approval of the agency's board of governors, to remove from safeguards nuclear materials to be used in non-proscribed military activities such as naval nuclear propulsion. This possibility limits the power of the agency to enforce the primary goal of the safeguards agreement, i.e., to verify that nuclear materials are not diverted to pursue the development of nuclear weapons or other nuclear explosive devices. Brazil will soon be the first non-nuclear weapons state to deploy a nuclear submarine and the first to challenge the nonproliferation regime to verify the non-diversion of nuclear material from a military activity. As part of a strategy to address this important issue, and after reviewing the existing legal framework, this paper presents a model for the application of safeguards on the naval nuclear fuel cycle in a military environment. The model could potentially be used for Brazil's naval fuel cycle but also be universally applicable to other non-nuclear weapon states and potentially to nuclear weapon states.

A Discontinuity in the Safeguards Regime?

The consequences for the nuclear nonproliferation regime of the spread of military nuclear-propelled vessels, including nuclear submarines, to non-nuclear weapons states (NNWS) have been a recurring concern for more than twenty-five years.[1] The current concerns focus on Brazil's nuclear submarine program and Iran's declared interest in naval nuclear programs.[2] Germany and Japan, both NNWS, developed nuclear naval propulsion in the 1960s and 1970s but for civilian applications.[3]

At the heart of this apprehension is the interpretation of Paragraph 14 in the standard safeguards agreements between the International Atomic Energy Agency (IAEA) and NNWS parties to the treaty on the Nonproliferation of Nuclear Weapons (NPT).[i] Paragraph 14 is the legal framework for the non-application of safeguards to nuclear material to be used in non-proscribed military activities such as nuclear propulsion:

> "NON-APPLICATION OF SAFEGUARDS TO NUCLEAR MATERIAL TO BE USED IN NON-PEACEFUL ACTIVITIES
>
> 14. The Agreement should provide that if the State intends to exercise its discretion to use nuclear material which is required to be safeguarded thereunder in a nuclear activity which does not require the application of safeguards under the Agreement, the following procedures will apply:
>
> (a) The State shall inform the Agency of the activity, making it clear:
>
> (i) That the use of the nuclear material in a non-proscribed military activity will not be in conflict with an undertaking the State may have given and in respect of which Agency safeguards apply, that the nuclear material will be used only in a peaceful nuclear activity; and
>
> (ii) That during the period of non-application of safeguards the nuclear material will not be used for the production of nuclear weapons or other nuclear explosive devices;
>
> (b) The Agency and the State shall make an arrangement so that, only while the nuclear material is in such an activity, the safeguards provided for in the Agreement will not be applied. The arrangement shall identify, to the extent possible, the period or circumstances during which safeguards will not be applied.

> In any event, the safeguards provided for in the Agreement shall again apply as soon as the nuclear material is reintroduced into a peaceful nuclear activity.
>
> The Agency shall be kept informed of the total quantity and composition of such unsafeguarded nuclear material in the State and of any exports of such material; and
>
> (c) Each arrangement shall be made in agreement with the Agency. The Agency's agreement shall be given as promptly as possible; it shall only relate to the temporal and procedural provisions, reporting arrangements, etc., but shall not involve any approval or classified knowledge of the military activity or relate to the use of the nuclear material therein."

This paragraph, often referred to in the nonproliferation literature as the "NPT loophole," is presented as an opportunity for NNWS to remove nuclear material from safeguards and process it beyond the reach of IAEA verification activities. At the time of negotiations on Paragraph 14, this concern was also raised by the IAEA Board of Governors' Safeguards Committee, who tried: "to avoid a situation where withdrawals of nuclear material from safeguards for non-proscribed military use could become a loophole allowing use for nuclear explosive purposes, beyond the reach of agency verification activities".[5] This "loophole" is depicted by critics as a "threat" to the NPT regime and seen as permitting the indiscriminate spread of non-proscribed nuclear military activities (henceforth NPMA), especially the proliferation of nuclear vessels, among NNWS and so increasing the risk of fissile material diversion for possible nuclear weapon purposes. A careful reading of Paragraph 14 leads to a more nuanced picture, however.

Paragraph 14 identifies a beginning and an end to the non-application of safeguards. It requires the state to keep the IAEA informed on the quantity and composition of nuclear materials withdrawn from safeguards. Paragraph 14 arrangements require the approval of the IAEA. In particular:

- The state must inform the IAEA of the NPMA for which it needs to call for the special dispositions of Paragraph 14 (non-application of safeguards), making it clear that during the period of the non-application of safeguards the materials will not be used for the production of weapons.
- Safeguards must be reapplied on the nuclear material as soon as it is reintroduced into peaceful activities.
- The IAEA must be kept informed of the total nuclear material inventory out of safeguards, including quantities and composition.
- Any such arrangement must be made in agreement with the IAEA and would be submitted to the IAEA Board of Governors for approval.[6]
- The IAEA is prohibited from gaining access to classified information related to the activity in question.

Yet, if Paragraph 14 gives a legal basis to deal with NPMA within the NPT, it also clearly limits the power of the agency to enforce the primary goal of the safeguards agreement, i.e., to verify that the nuclear material is not diverted to nuclear weapons or other nuclear explosive devices. Once safeguards are removed, the verification regime is undermined, and the treaty cannot be fully enforced.

In the case of applications related to naval nuclear propulsion, this situation is of particular concern since most of the current nuclear-powered vessels deployed around the world are fueled with highly enriched uranium (HEU, ≥ 20 percent uranium-235), a directly weapon-usable nuclear material.[7]

Consequently, under the current rules of the NPT safeguards regime, a country wishing to develop an HEU-fueled nuclear-powered military vessel would potentially have the right, if granted by the IAEA, to stockpile unsafeguarded fissile material and process it in unsafeguarded facilities without breaching its safeguards agreement.

While it seems difficult to prevent further countries from acquiring nuclear submarine technology, actions can be taken to ensure that nuclear materials used in naval nuclear reactor fuel cycles are not diverted for weapons purposes. One step forward would be to promote the establishment of an international norm limiting the enrichment of naval nuclear fuel to low-enriched uranium (LEU) level, i.e., enriched to less than 20 percent U-235, and therefore limiting the risks of direct weaponization of diverted fissile material. In this case, assuming that enrichment facilities are under standard IAEA safeguards, a country would need to enrich parts of its naval stockpile of LEU to HEU levels clandestinely, something that could potentially be detected.

Unfortunately, the reluctance of various navies — especially that of the United States — to design their future naval nuclear reactors using LEU fuel, could jeopardize any effort in this direction.[8]

It is important to note that the technology to power nuclear vessels with LEU exists and is already deployed. France is currently operating eleven nuclear vessels (ten submarines and one aircraft carrier), all fueled with LEU, and plans to continue to do so in the future. The next class of French nuclear attack submarines (SSN Suffren, to be commissioned in 2017) is supposed to be fueled with uranium enriched to levels used in civilian light water nuclear power plants.[9] This strategy of using LEU fuel should be encouraged in current and future navies operating naval nuclear reactors.

Ultimately, even if no consensus can be reached on limitation of enrichment to below 20 percent U235 for NPMA, the only way to efficiently and comprehensively guarantee that no naval fuel is diverted for weapons purposes would be to promote the implementation of nonintrusive safeguards in the naval nuclear fuel cycle. This approach, which appears quite challenging at first but would greatly reinforce the verification regime, is the main focus of this paper.

After discussing constraints on the implementation of safeguards in a military environment — especially with regard to the protection of military secrecy — this paper presents a model for the application of safeguards to a military naval reactor fuel cycle. Each step of the fuel cycle is addressed from the enrichment and fabrication of the fuel to spent fuel disposal. Particular attention is given to the design of the naval base and the implementation of safeguards in the fueling/defueling process of the naval reactor while protecting inspectors from gaining access to classified knowledge. Without loss of generality for certain key concepts and because Brazil will be the first NNWS to deploy a nuclear submarine, the application of the model is primarily focusing on the future Brazilian military naval nuclear fuel cycle.

Since the approach proposed here in its most general form applies to monitoring the military naval fuel cycle and does not depend on whether the fuel is LEU or HEU it can be extended to nuclear-powered vessels deployed by weapon states. A future Fissile Material Cutoff Treaty (FMCT) will need to provide assurance that highly enriched uranium intended for military naval propulsion is not diverted for weapons.

The Brazilian Case

In early 2013, Brazilian President Dilma Rousseff declared during the inauguration of the new Brazilian naval shipyard in Rio: "We are entering the select club of countries with nuclear submarines: The United States, Russia, France, Britain, and China."[10] So far this "select club," which also includes India, has been composed of only nuclear weapon states (NWS). Brazil will be the first NNWS to pursue a non-proscribed military application of atomic energy. This poses a challenge to the IAEA to come up with a good strategy to assure the non-diversion of nuclear materials used in NPMA.

Brazil has not signed an INFCIRC/153 comprehensive safeguards agreement with the IAEA. For Brazil, safeguards are defined by an equivalent document, usually referred as "the Quadripartite Agreement," co-signed by Argentina, Brazil, the Brazilian–Argentine Agency for Accounting and Control of Nuclear Materials (ABACC), and the IAEA.[11] Following the accession of Brazil to the NPT in 1998, the IAEA's Board of Governors declared INFCIRC/435 to satisfy the obligation of Brazil under Article III of the NPT.[12]

> The equivalent of Paragraph 14 in INFCIRC/153 is Article 13 in INFCIRC/435:
>
> "Article 13
>
> If a State Party intends to exercise its discretion to use nuclear material which is required to be safeguarded under this Agreement for nuclear propulsion or operation of any vehicle, including submarines and prototypes, or in such other non-proscribed nuclear activity as agreed between the State Party and the Agency, the following procedures shall apply:
>
> (a) that State Party shall inform the Agency, through ABACC, of the activity, and shall make it clear:
>
> (i) that the use of the nuclear material in such an activity will not be in conflict with any undertaking of the State Party under agreements concluded with the Agency in connection with Article XI of the Statute of the Agency or any other agreement concluded with the Agency in connection with INFCIRC/26 (and Add. l) or INFCIRC/66 (and Rev. l or 2), as applicable; and
>
> (ii) that during the period of application of the special procedures the nuclear material will not be used for the production of nuclear weapons or other nuclear explosive devices;

(b) the State Party and the Agency shall make an arrangement so that, these special procedures shall apply only while the nuclear material is used for nuclear propulsion or in the operation of any vehicle, including submarines and prototypes, or in such other non-proscribed nuclear activity as agreed between the State Party and the Agency. The arrangement shall identify, to the extent possible, the period or circumstances during which the special procedures shall be applied. In any event, the other procedures provided for in this Agreement shall apply again as soon as the nuclear material is reintroduced into a nuclear activity other than the above. The Agency shall be kept informed of the total quantity and composition of such material in that State Party and of any export of such material; and

(c) each arrangement shall be concluded between the State Party concerned and the Agency as promptly as possible and shall relate only to such matters as temporal and procedural provisions and reporting arrangements, but shall not involve any approval or classified knowledge of such activity or relate to the use of the nuclear material therein."

From a reading of Article 13, it is not clear if what is mentioned as "special procedures" is equivalent to the non-application of safeguards in Paragraph 14. The IAEA safeguards glossary doesn't specify this term neither does it refer to INFCIRC/435.[13]

However, sub-paragraph (b) specifies the following: "the special procedures shall apply only while the nuclear material is used for nuclear propulsion or in the operation of any vehicle, including submarines and prototypes." This sentence means that only when the fuel is physically in the submarine reactor and the reactor is operating, the fissile material can be potentially exempt from safeguards. Consequently any activities related to fuel fabrication, storage, and disposal should be safeguarded. This would be an important difference between INFCIRC/153 and INFCIRC/435.

Nevertheless, even if the Brazilian case may seem less severe due to this difference, the gravity of the issue and its potential implications for other NNWS should encourage the IAEA to seek a universally applicable agreement to all NNWS in its future arrangement with Brazil. This agreement could take the form, for example, of an additional protocol for the safeguards of non-proscribed military activities. Whether or not Brazil will be treated as a special case by the IAEA, the safeguards model presented here could be applied in a non-discriminatory manner to any NNWS including Brazil and potentially to any NWS. Interestingly, thanks to the particular provisions of INFCIRC/435, Brazil could become a model for NNWS parties to the NPT in showing the possibility to implement non-intrusive safeguards for NPMA.

Military Secrecy Baseline for the Implementation of Safeguards

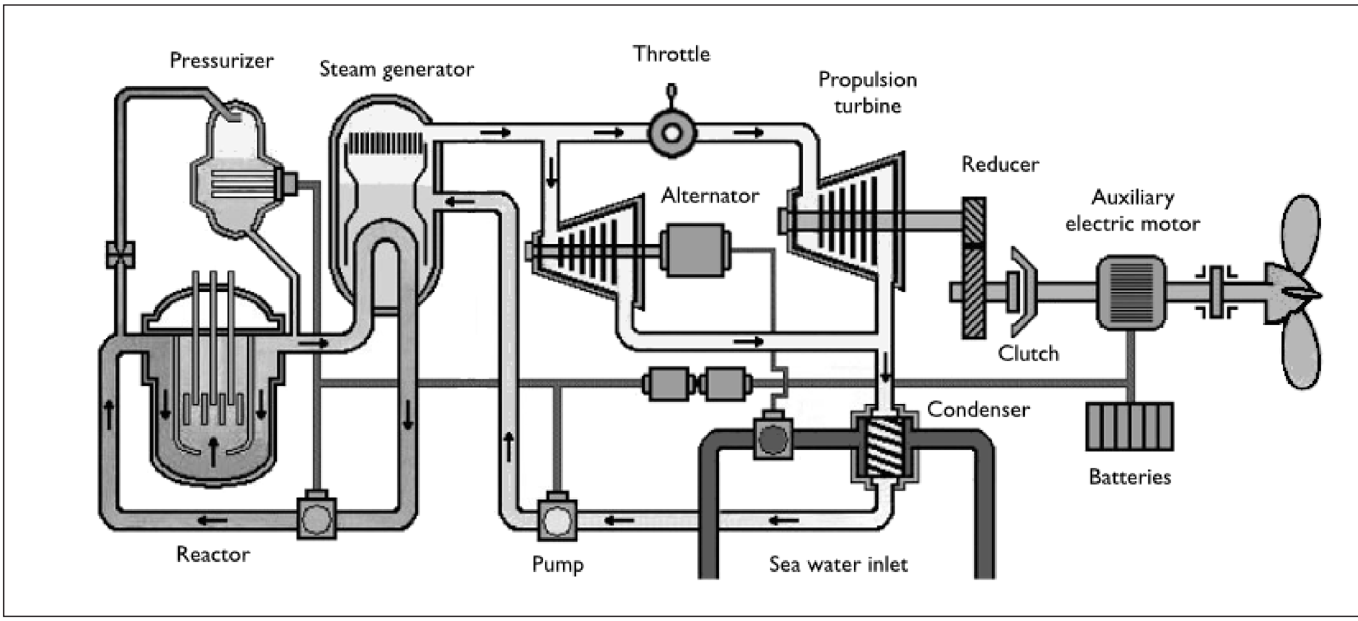
The first obstacle to the implementation of safeguards in the naval nuclear fuel cycle is the need to protect military information considered classified or sensitive by the host state and as required by Paragraph 14. It is therefore important to arrive at a reasonable agreement on what information should stay classified and protected and what information must be shared with the IAEA to ensure effective implementation of safeguards.

Four main issues need to be addressed:

- Information with regard to fuel design and composition;
- Information with regard to the naval reactor designs;
- Information with regard to operational military installations, i.e., naval bases; and
- Information with regard to the military fuel cycle fabrication facilities, i.e., processes.

Naval reactors and their associated fuel are designed to meet certain military requirements that differentiate them from civilian power reactors, such as the ability to allow rapid power transients, to operate in the naval environment (e.g., mechanical shocks from collisions, vibrations from waves while on the surface, changes in vessel inclination while diving) and resist external shocks (e.g., a depth charge explosion close to a submarine), and to operate silently by limiting noise radiation and propagation to the hull. Thus the design of the fuel and the core in general (shape, cladding, and matrix materials together) may intrinsically contain a limited amount of information on the overall military performance of a submarine. It is understandable that the host state will want to minimize access to such information during the implementation of safeguards.

Figure 1. Schematic of a nuclear submarine propulsion system. The propulsion of the submarine can be achieved for example by "direct" coupling of the steam turbine to the propeller shaft or by generating electricity to drive electric motors.[14]



Some information crucial for material accountancy need not be classified, however. For example, while the total uranium-235 inventory of a fresh core can give an upper bound for the maximum lifetime a reactor can achieve before refueling, it gives no indication of the actual tactical performance of the submarine propulsion system.

As any thermodynamic cycle, this performance depends on many parameters including the efficiency in converting heat to mechanical power (see Figure 1).

It is important to also note that the gross external dimensions of a fuel element shouldn't be required to be classified, as they don't by themselves give information on the thermal-hydraulic properties of the fuel.[15]

In what follows, and in line with the reporting obligation of the state, we will assume that the IAEA will be informed of and be able to verify non-intrusively the total U-235 and U-238 inventory of a core.

A "managed access" for inspectors to military fuel storage facilities should be organized in a way to protect both classified fuel design information and sensitive operational information.[16] The term operational information refers here to all information related to a naval base's operational status, such as internal ship design, ship movements, weaponry, and military personnel not easily available from commercial publications and satellite imagery. Inspectors should only have access to the information they need to implement the naval nuclear fuel safeguards agreement. The deployment of local remote monitoring technologies on the naval base in areas where the inspectors are given routine access should be encouraged, as they could provide continuity of safeguards at times of active military operations when physical access of IAEA inspectors could be more limited.

A Model for Safeguarding Military Naval Nuclear Fuel

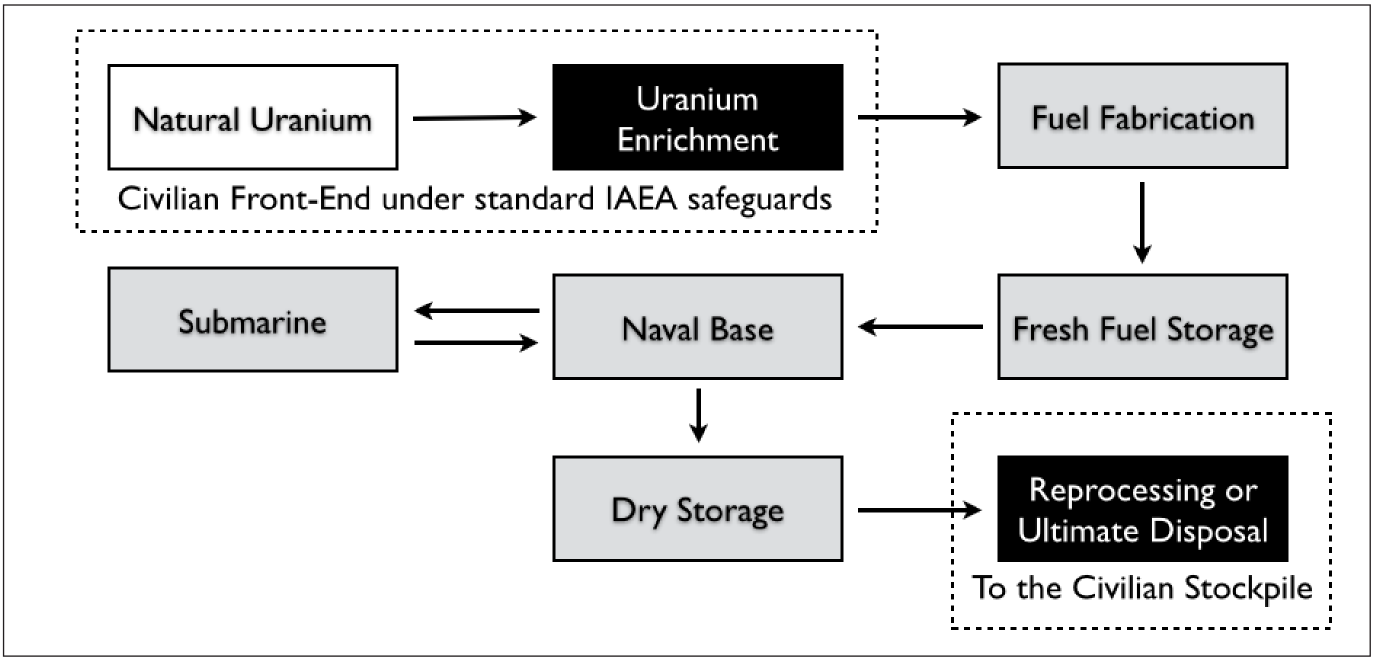
A Fuel Cycle Approach

We approach the problem from a fuel cycle point of view, meaning that we will look at every step in the naval fuel cycle and propose associated safeguards to ensure the non-diversion of enriched uranium for any other purposes.[17]

Figure 2 presents the key steps of the naval fuel cycle: natural uranium procurement, uranium enrichment, fuel fabrication, transfer to a naval base, fueling of the naval reactor, reactor operation, defueling, and pool storage on the naval base, then dry storage followed eventually by disposal or reprocessing. For the potential application of safeguards in a NWS as part of a FMCT, another path for uranium procurement would potentially need to be added: the supply of enriched uranium from pre-existing military stockpiles.

We have defined three different stockpiles between which materials can be transferred (Figure 3): civilian stockpiles subject to standard IAEA safeguards, a safeguarded naval fuel

Figure 2. A simple model of the naval fuel cycle for a submarine in a NNWS



stockpile subject to the rules that will be established in our model, and an unsafeguarded uranium stockpile. The unsafeguarded stockpile is a peculiarity of NWS and represents all the uranium that is not under safeguards such as weapon-grade HEU or previously produced naval fuel. The application of the model to NWS would not require any pre-declaration of unsafeguarded stockpiles.

For NNWS, everything that enters the safeguarded naval fuel stockpile must end up in the safeguarded civilian uranium stockpile as required by Paragraph 14 of the safeguards agreement. This rule could also be applied to NWS in order to avoid "double standards" between NNWS and NWS. This way, if the fuel is obtained from HEU weapon-usable material, NWS can eliminate in a verifiable manner the surplus of their weapon-usable fissile material stockpiles. It is important to note that in the context of a FMCT, NWS will be required to carry out uranium enrichment even for naval application in safeguarded civilian facilities.

In what follows, we will focus on the case of Brazil only and will not pursue the implementation of safeguards in NWS as part of a FMCT. The latter issue is the focus of future research.

Assumptions on the Brazilian Case

We assume that Brazil will use LEU naval fuel and that its reactor core will be composed of several fuel elements as opposed to a one-element core.[18] This assumption is backed up by information published in the literature about Brazil's Labgene prototype naval reactor. The 48-MWth reactor has a cylindrical core of twenty-one standard-size pressurized water reactor (PWR) fuel elements.[19] The Brazilian navy presented several mock-ups of the future SSN, its reactor vessel (code name 2131-R) as well as a 1:1-scale fuel element for the naval reactor during an international defense and security exhibition held in Brazil in April 2013 (see Figures 4 and 5).[20] Table 1 presents the design characteristics of this fuel element. With these characteristics and assuming twenty-one fuel elements, the total uranium inventory of a core would be about 2,700 kg of uranium.

Figure 3. Material flow between national stockpiles. The unsafeguarded uranium stockpile exists for NWS only.

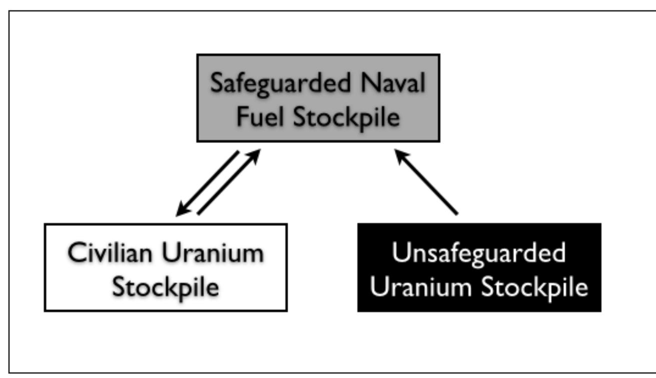


Table 1. Design characteristics of the alleged Brazilian nuclear reactor fuel element. The element is similar to a standard PWR element.

Arrangement	# of fuel rods	# of control rods	# of UO2 pellets	Total mass of UO2 (kg)	Dimensions (mm)
17x17	260	29	24,440	146	220x220x1455

Figure 4. Mock-up of the first Brazilian SSN

The Labgene reactor features the same equipment and arrangement as a two-loop naval nuclear reactor design that can be integrated in a submarine hull, as seen in Figure 6. The mock-up of the Brazilian SSN features a large hatch in the hull above the reactor compartment (Figure 4).

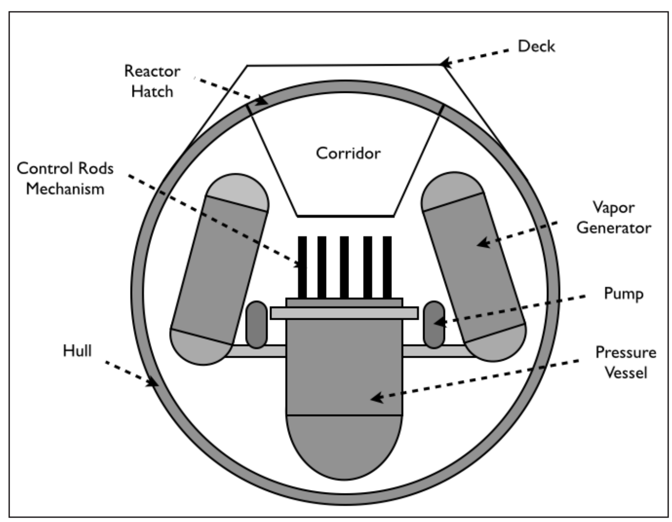
It seems very unlikely that the naval reactor on board of the first Brazilian SSN will differ significantly from the prototype land reactor. If the presence of standard-size fuel elements (not necessarily having fuel pins but also plates as is the case for cermet fuel) is confirmed in the future, it would be easier for IAEA inspectors to verify the uranium inventory using for example standard measurement methods such as the uranium neutron coincidence collar (UNCL).[21]

The first "typical PWR" fuel element presented above may be too weak from a structural point of view to be used in an operational submarine. Additional information from an official of the Brazilian nuclear power company, Eletronuclear, confirms that Brazil is exploring two alternative types of LEU fuel (caramel and cermet fuel) to produce a second reactor core.[22]

As mentioned above, we assume that the future Brazilian nuclear submarine will feature a large reactor hatch to facilitate fueling and defueling operations based on a model reported in the literature used in French nuclear submarines.[23] This last assumption is based on the fact that the French shipbuilding company, DCNS, will assist Brazil in the construction of its first nuclear submarine, giving advice on the non-nuclear parts of the submarine and potentially the reactor integration in the hull.[24] The Brazilian navy should see this reactor-hatch technology as crucial if it wishes to refuel the reactor in short periods of time (of the order of weeks).[25] All things considered, it is important to note that the model presented here remains mostly hypothetical.

Figure 5. Mock-ups of the 2131-R reactor (left) and the first generation fuel element (right)

Figure 6. Integration of a two-loop naval nuclear reactor design in a submarine hull



In what follows, we go through each step in the naval fuel cycle and present a strategy for the implementation of safeguards, starting with the civilian front end.

The Civilian Front End

The civilian front end covers activities that are under standard IAEA safeguards in a NNWS, such as uranium enrichment. After uranium enters the naval fuel stockpile, no further enrichment operations are permitted, only the blending of uranium at different enrichments is allowed. Uranium enrichment being one of the most sensitive operations with regard to nonproliferation (together with plutonium extraction from irradiated fuel), it must remain outside any military facility in order to build confidence in the ability to detect any non-declared enrichment activity. Furthermore, this policy towards enrichment implies that an enrichment facility declared to be safeguarded cannot be used to enrich unsafeguarded uranium.[26]

Militarization of the Fissile Material

The militarization of the nuclear material is the crucial step where the uranium leaves the civilian stockpile to enter the naval fuel stockpile. This happens within the naval fuel fabrication plant. All the uranium that enters the naval fuel stockpile must go through this process. Entering uranium is in an unclassified form. Information on the total amount of uranium and its exact isotopic composition would be measured and registered. A document shared with the agency would certify that a certain amount of uranium with a particular enrichment had left the country's civilian stockpile and entered the naval fuel stockpile.[27] This process would require the presence of inspectors.

Fuel Fabrication and Fresh Fuel Storage

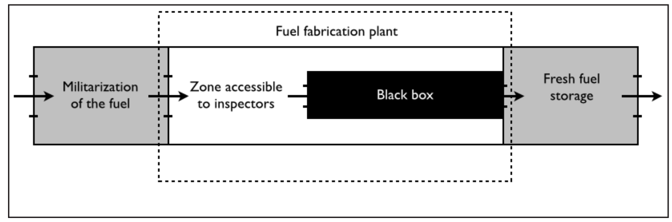
As soon as uranium enters the safeguarded naval fuel stockpile, it can be processed and transformed into fuel elements or a complete core. The fuel fabrication facility is where the material may be converted to a classified form.

In the trivial case where a state decides that the design of its fuel elements is unclassified, it would be easy to implement a safeguards system similar to that in the civil sector that would identify each fuel element. Inspectors could assay the quantity and enrichment of the uranium in the fuel and thereby would be able to verify the material balance between what goes in and out of the fuel fabrication plant. It seems that Brazil may head in this direction.

However, if a state chooses to classify the design of its fuel elements, then performing such material balance checks becomes harder. As discussed earlier, we assume that two main attributes will be classified, the exact composition of a fuel element (including non-fissile materials) and its detailed geometrical shape (for example, its internal dimensions).[28]

Figure 7 describes the layout of a hypothetical fuel fabrication facility that has features that would both facilitate the fissile materials safeguarding process and protect sensitive fuel information. The facility is divided into three principal volumes.

Figure 7. Fuel fabrication facility (hypothetical layout)



One, the "black box," is dedicated to the militarization process of the uranium as explained earlier. The zone is divided in two areas, one that is accessible to the inspectors, the second is the black box and can only be accessed by inspectors when no production is occurring and no uncovered fuel is present. The third area is the fresh fuel storage where fuel elements await shipment to the naval base.

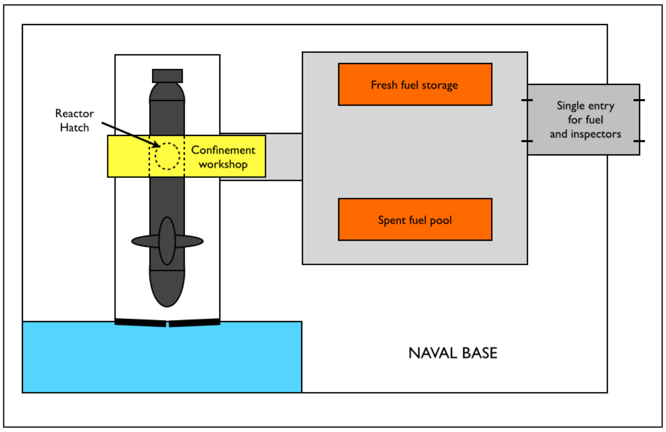
The black box area is the place where the fuel is converted to a classified form. This area, which is not accessible to inspectors during production, must be as simple as possible, for example with a single point-of-access.[29] It is important to stress that not all the fuel fabrication process need be classified; for example, in the case of caramel fuel manufacturing, it is public knowledge that this type of fuel is made of small flat rectangular uranium dioxide tablets; thus the production line of those tablets would not require to be located in the black box.[30]

The black box is connected to the fresh fuel storage area, which is constantly monitored by cameras. Fuel elements exit the black box in a specially designed transportation cask that protects the design of the fuel element from inspectors' eyes. The inspectors could, however, use an active interrogation system to determine the content of U-235 of every cask and apply seals on all of them.[31] One can imagine a measurement technique where, as a fuel element would be placed into a cask, the uranium content could be measured using an adapted UNCL system at the mouth of the cask.

The material balance of the fuel fabrication plant can then be made to ensure that no material has been diverted. This would require the inspectors to verify that no nuclear material is unaccounted for within the black box once fuel elements production has been completed.

Since the complete U-235 inventory of the reactor core will be declared by the state, the IAEA could report any abnormal increase in activity within the plant (i.e., a state manufacturing three cores for only one submarine). A NNWS could be required to agree with the IAEA on a cap on the size of the naval fuel stockpile, for example, limiting the stockpile to two

Figure 8. Model of the naval base. The mobile workshop links the fuel storage building to the submarine (over the reactor hatch) during refueling operations.



cores per reactor operated in the fleet (one in the vessel, and one in the stockpile). A typical 50 MWth naval reactor, working for 600 full power days and assuming a U-235 burn-up of half the initial inventory, has an initial core inventory of 1,125 kg of LEU enriched at 7 percent U-235.

Finally, only fuel elements accounted for and properly sealed can be transported from the fresh fuel storage area to the naval base. The IAEA would be kept informed of the cask movements at all times.

Design of the Naval Base

Figure 8 presents a conceptual layout of the facilities on the naval base. There is only one entry for the naval fuel and for the inspectors on to the base, which leads directly to the fuel storage building. This simple feature limits inspectors' access to other areas of the base, protecting classified operational information.

The fuel storage building is composed of three main areas: a fresh fuel storage area, a spent fuel pool, and a confinement workshop. The guarantee of non-diversion of fissile materials would mostly rely on cask sealing and tagging as well as random assaying of stored casks. Cameras could record the activity within the building as a complementary measure.

Fuel elements waiting to be transferred to the submarine reactor vessel are stored in the fresh fuel area. The amount of material is limited to one complete core. The spent fuel discharged from the reactor is temporarily stored in the spent fuel pool awaiting shipment to a dry cask storage area when residual heat would be low enough to permit transport. The inspection of fuel elements tags and seals in the pool could be conducted using for example the existing IAEA portable underwater television system (UWTV).[32]

The defueling and refueling processes are designed to ensure continuity of knowledge on the use of the fuel elements as well as to protect classified information with regard to the reactor and the submarine. The protocol could be as follows:

> The state would inform the IAEA that a defueling or refueling operation has been scheduled. The state would prepare the operation before the inspectors were allowed to enter the fuel storage building. The confinement workshop would be placed above the submarine located in dry dock right above the reactor compartment (Figures 8 and 9). The workshop would then be connected to the submarine hull to ensure confinement.

We start with the defueling operation. The reactor hatch is presented to the inspectors before being opened. Mechanical seals may have been placed on top of the hatch but under the submarine deck to ensure that the hatch is not opened in the absence of an IAEA inspector.[33] Once the inspectors attest that the seals were not broken, the reactor hatch can be opened. The inspector leaves the facility, and the state can start the operation of opening the reactor pressure vessel.

Once various reactor elements have been removed, for example the pressure vessel top and the control rods mechanisms (see Figure 6), the fuel elements can be removed from the pressure vessel. Figure 9 shows the reactor compartment configuration during defueling operations. A large cylinder is connected to the pressure vessel and filled with water up to the level of the reactor hatch to protect the operators from radiation while spent fuel is transferred from the pressure vessel into a cask under water.

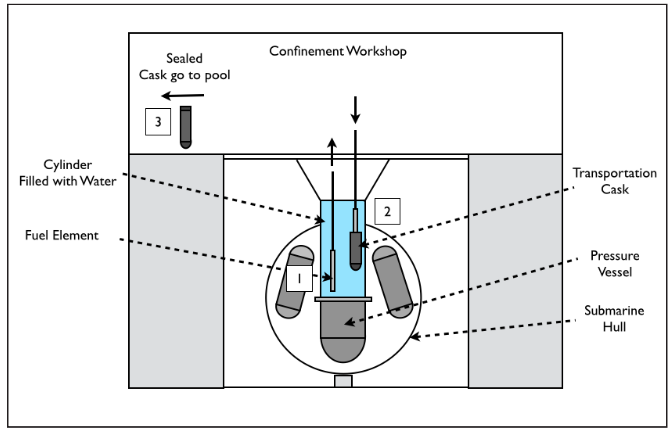
When the state is ready to move the fuel elements out of the vessel, the inspectors can be invited again into the building to follow the operations. Each fuel element is transferred to a cask inside the water (see Figure 9), and the cask is then taken out and moved to the spent fuel pool.[34] The spent fuel cask, which could be different from a fresh fuel cask, protects the operator from radiation during the transfer and guarantees protection for the classified fuel element design. The inspectors seal every spent fuel cask. Before doing so a neutron and/or gamma profiling of randomly selected fuel elements could be made using a cask radiation profiling system.[35] This would allow re-verifying the content of the casks at a later stage by comparing new radiation profiles to the baseline fingerprints. Consistency between fingerprints indicates that the spent fuel elements have remained undisturbed.

At the end of the transfer process, the inspectors verify the absence of irradiated fuel in the pressure vessel, using for example a gamma detector looking for the 757/766 keV line from $^{95}Nb/^{95}Zr$ mounted on a handling pole.[36] No visual check of the interior of the pressure vessel would be required.

The fueling operation works on the same concept but in reverse. At the end of the fueling operation, inspectors affix seals on the reactor hatch.

Submarines are usually fueled with a complete fresh core, but they could also use fuel elements shuffling technique to maximize the fuel burnup of each element.[37] This should not be a problem as the IAEA should be able to keep track of the material inventory of the core and the fuel storage building.

Figure 9. Operations during defueling of the reactor: the fuel elements are removed from the pressure vessel inside the cylinder filled with water and then placed in transportation casks. Once sealed, the casks are transferred to the spent fuel pool.



Spent Fuel Storage and Demilitarization of the Fuel

After spending a certain amount of time on the naval base in the spent fuel pool to allow reduction of their radioactive decay heat, fuel elements could be transferred to another storage area, including both a spent fuel pool and dry storage area. Once the fuel elements leave the naval base, they are not allowed to be fuel again in a submarine.

Again all movement of casks should be declared to the IAEA. It would be convenient if the casks stayed the same throughout the back end of the fuel cycle. Once seals are applied upon discharging the spent fuel from submarine reactor, they would not have to be removed unless the fuel is reprocessed. Thermal imaging techniques could be used to monitor the casks in the dry storage area. This technique measures the decay heat of the spent fuel in the cask, but does not reveal design information.

Earlier, we mentioned that the fissile materials should ultimately go back to the civilian stockpile under standard IAEA safeguards. There would be two ways to do so: first, the spent fuel kept in its original cask could be moved to and permanently sealed and stored in a "civilian stockpile" facility under IAEA safeguards; this material could eventually be prepared for final disposal in a geological repository. Second, the fuel could be reprocessed in a reprocessing facility.[38] The products of the reprocessing process would then go back to the civilian stockpile. In both cases, the material would be transferred back to the civilian stockpile, leaving permanently the naval nuclear fuel cycle safeguards system and keeping the size of the naval fuel stockpile at a reasonable level.[39]

Conclusion

With Brazil on the way to becoming the first non-nuclear weapon state to deploy military naval nuclear propulsion, the right of non-nuclear weapons states to withdraw material from safeguards for use in military applications is a potentially serious proliferation problem. NPT member states wish to ensure that no fissile material is diverted for weapon purposes by any non-weapon state parties of the treaty. To meet this goal in the case of Brazil's naval fuel cycle will require that the International Atomic Energy Agency for the first time extend its safeguards activity into a military environment.

This paper shows that the implementation of safeguards in a military environment, while not easy, may be less challenging than seems to be widely assumed. The model presented shows how it may be possible to track the flow of fissile materials from enrichment through fuel fabrication and fresh fuel storage to the submarine reactor and eventual spent fuel storage and demilitarization of the fuel. It proposes in particular the use of a "black box" approach for fuel fabrication and the careful design of the submarine reactor fueling facility at a naval base to manage the access of inspectors and protect classified information.

The example presented in this paper applies only to a particular submarine architecture and focuses on Brazil. A similar approach could be pursued for other nuclear submarines' designs and surface ships, including those equipped with highly enriched uranium lifetime core, in weapons states and would be relevant for a Fissile Material Cut-Off Treaty.

Since Brazil is not the only non-weapons state interested in military nuclear naval propulsion, the International Atomic Energy Agency should be encouraged to seek a universally applicable agreement on naval nuclear fuel safeguards. This agreement could take the form, for example, of an additional protocol for the safeguards of non-proscribed military activities.

Acknowledgments

The author wishes to thank Frank von Hippel, Zia Mian, and Alexander Glaser from Princeton University for their comments and guidance throughout the completion of this work as well as Olli Heinonen from Harvard University for his comments and advice on an earlier draft of this article.

Sébastien Philippe is a Ph.D. candidate in Princeton University's Department of Mechanical and Aerospace Engineering. He is working within the Nuclear Futures Laboratory on verification technologies and is affiliated with the university's program on Science and Global Security in the Woodrow Wilson School of Public and International Affairs. Prior to joining Princeton, Philippe worked for two years in the French Ministry of Defense. He received his M.S.E. in mechanical and design engineering from the French National Institute of Applied Sciences (INSA, Lyon) in 2010 and a B.A.I. from Trinity College Dublin in 2009 as part of a joint European degree program.

References and End Notes

1. Desjardins, M.-F., and T. Rauf. 1988. Opening Pandora's Box? Nuclear-powered Submarines and the Spread of Nuclear Weapons. *Aurora Papers*. Ottawa: Canadian Centre for Arms Control and Disarmament.
2. Thielmann, G., and S. Kelleher-Vergantini. 2013. The Naval Nuclear Reactor Threat to the NPT. *Threat Assessment Brief*. Arms Control Association.
3. Fribourg, C. 2002. Réacteurs Nucléaires de Propulsion Navale. *Techniques de L'ingénieur,* no. BN3141.
4. IAEA. 1974. INFCIRC/153 - The Structure and Content of Agreements Between the Agency and States Required in Connection with the Treaty on the Nonproliferation of Nuclear Weapons, 4, 25,"schema":"https://github.com/citation-style-language/schema/raw/master/csl-citation.json"}
5. International Energy Associates. 1984. Review of The Negotiating History of the IAEA Safeguards Document INFCIRC/153. The Arms Control and Disarmament Agency.
6. IAEA. 2001. IAEA Safeguards Glossary. *International Nuclear Verification Series, 3*.
7. Ma, C., and F. von Hippel. 2001. Ending the Production of Highly Enriched Uranium for Naval Reactors. *The Nonproliferation Review*, 86–101.
8. This reluctance was first reflected in the following report: Office of Naval Nuclear Propulsion. June 1995. *Report on Use of Low Enriched Uranium in Naval Nuclear Propulsion*. And again more recently in an updated version: Office of Naval Reactors. January 2014. *Report on Low Enriched Uranium for Naval Reactor Cores.*
9. Ministère de la Défense. December 22, 2006. Le Programme Barracuda, Le Sous-Marin d'Attaque du 21ème Siècle, Dossier de Presse. It is important to note that France does not have any military (or unsafeguarded) enrichment capacity since it shut down the Pierrelatte plant in 1996 (HEU) and the "George Besse 1" plant in 2012 (LEU). Naval reactor fuel can thus only be manufactured using uranium previously enriched or freshly produced LEU limited to ≤6 percent U-235 from the civilian plant "George Besse 2".
10. Interestingly, the Brazilian president omits India in her list, see: AFP. March 1, 2013. Brazil to get its first nuclear subs.
11. IAEA. 1991. INFCIRC/435 — Agreement of 13 December 1991 Between the Republic of Argentina, the Federative Republic of Brazil, the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials and the International Atomic Energy Agency for the Application of Safeguards.
12. IAEA. 2000. INFCIRC/435/Mod.3 — An Agreement by Exchange of Letters with the Federative Republic of Brazil in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons and the Treaty for the Prohibition of Nuclear Weapons in Latin America and the Caribbean.
13. IAEA. 2001. IAEA Safeguards Glossary. *op. cit*.
14. Fribourg, C. 2002. Réacteurs Nucléaires de Propulsion Navale. *op. cit*.
15. By gross external dimensions, we mean, for example, the smallest rectangular box that would contain the fuel element.
16. The definition of "managed access" as given in the IAEA Safeguards glossary (*op. cit.*) is extended here to the protection of military classified information.

17. Common IAEA safeguards techniques and equipment based on material accountancy, containment and surveillance as well as environmental sampling are described in: IAEA. 2011. Safeguards Techniques and Equipment: 2011 Edition.
18. For a description of various naval nuclear reactor concepts see: Fribourg, C. 2002. Réacteurs Nucléaires de Propulsion Navale. *op. cit*. Note that the volume of an attack submarine reactor core is of the order of 1 m^3.
19. Dos Santos Guimarães, L. 2005. Completion of Fabrication and Assembly of the Internals and Pressure Vessel of the LABGENE Reactor. *Economia & Energia* and De Carvalho, L.S., and J. M. de Oliveira Neto. 2009. Advanced Technology Application Station Blackout Core Damage Frequency Reduction – The Contribution of AN AC Independent Core Residual Heat Removal System. International Conference on Opportunities and Challenges for Water Cooled Reactors in the 21st Century. Vienna: IAEA.\\uc0\\u8221{} \\i Economia & Energia\\i0{}, January 2005; L.S. de Carvalho and de Oliveira Neto, J. M., \\uc0\\u8220{}Advanced Technology Application Station Blackout Core Damage Frequency Reduction \\uc0\\u8211{} The Contribution of AN AC Independent Core Residual Heat Removal System\\uc0\\u8221{} (presented at the International Conference on Opportunities and Challenges for Water Cooled Reactors in the 21st Century, Vienna: IAEA, 2009.
20. See the website: "LAAD Defence & Security," accessed August 27, 2013, http://laadexpo.com.br/english/. The pictures of the various mock-up are available on the official Brazilian Navy Flickr account: "Flickr: Marinha Do Brasil (Oficial)'s Photostream," accessed August 27, 2013, http://www.flickr.com/photos/mboficial/with/8642496037/.
21. The UNCL is a neutron coincidence counting based measurement device. It features a large collar that encloses a fresh fuel assembly and measure the linear mass density of uranium. It requires knowing the exact length of the assembly. See: IAEA.2011. Safeguards Techniques and Equipment: 2011 Edition, *op. cit*. Note that if the dimensions of the future fuel assemblies become too large, one could measure the uranium inventory on sub-elements before they get assembled in larger ones.
22. De Sá, A. 2013. *Brazil's Nuclear Submarine Program: Navigating the Uncharted Waters of NPT Safeguards.* Bachelor thesis, Princeton University.
23. Fribourg, C. 2001. Navires à Propulsion Nucléaire. *Techniques de L'ingénieur*, BN3140.
24. *Defense Industry Daily.* April 9, 2013. Brazil & France in Deal for SSKs, SSN.
25. Fribourg, C. 2001. Navires à Propulsion Nucléaire. *op. cit.*
26. This singular concept has been implemented in France for example in the Eurodif gaseous diffusion enrichment plant. The plant was under Euratom safeguards but unsafeguarded material was also processed in the facility. A 2002 Euratom report states that the "particular status" of the installation continues to limit the safeguards assurance and needs to be addressed." See: Commission of the European Communities. 2003. Report from the Commission to the European Parliament and the Council: Operation of Euratom Safeguards in 2002.
27. This is the "standard" procedure as referred in INFCIRC/153 (revised).
28. Note that as mentioned earlier the external dimensions do not need to be classified, which would facilitate in order the use appropriate measurement devices by the inspectors.
29. The black box area could potentially be accessible by inspectors after the end of any production campaign in order to verify that no quantities of uranium are being held there beyond acceptable losses to waste during the manufacturing process.
30. See, for example, the following advertising brochure for the use of caramel fuel in research reactors: CEA. 1979. *Le combustible caramel pour réacteurs de recherche*.
31. Note that in theory, each fuel element could have a different uranium isotopic composition.
32. IAEA. 2011. Safeguards Techniques and Equipment: 2011 Edition. *op.cit.*
33. This is similar to what is done in standard commercial light water reactors, see: Harms, N., and P. Rodriguez. 1996. Safeguards at Light-water Reactors: Current Practices, Future Directions. *IAEA Bulletin* 38, no. 4: 16–19.
34. Concept adapted from: Fribourg, C. 2001. Navires à Propulsion Nucléaire. *op. cit.*

35. This is a standard IAEA instrument usually used to re-verify the presence of spent fuel in casks following a break in the continuity of knowledge (i.e., gap in surveillance and seals), see: IAEA. 2001. Safeguards Techniques and Equipment: 2011 Edition. *op. cit*.
36. The detector could be the spent fuel attribute tester (SFAT) typically used by IAEA inspectors to detect the presence of spent fuel. Note that activation product such as ^{60}Co are identifiable with this instrument. See: IAEA. 2001. Safeguards Techniques and Equipment: 2011 Edition. *op. cit*.
37. Fribourg, C. 1999. La Propulsion Nucléaire Navale. *Revue Générale Nucléaire* no. 2: 32–49.
38. One could imagine the same "black box" concept as in the fuel fabrication facility. There, the fuel would for example be cut into pieces, leaving the black box in an unclassified form that could be assayed before any heavy metals and fission products would be separated preferably in a dedicated process line.
39. It could be interesting to set a time limit for which the spent fuel casks can be accounted in the naval fuel stockpile. For example, when the last submarine of a particular class is decommissioned, all remaining spent fuel cask in storage should be directly transferred to the civilian stockpile.

Spent Fuel Management: Daily Challenges and Long-term Planning

A Summary of the 29th INMM Spent Fuel Seminar
January 13-15, 2014

Carlyn Greene
Ux Consulting Company, LLC (UxC), Stone Mountain, Georgia USA

In mid-January 2014 nearly 120 nuclear industry experts convened in Washington, DC, USA, for the 29th Spent Fuel Seminar sponsored by the Institute of Nuclear Materials Management (INMM) and the U.S. Nuclear Infrastructure Council (NIC). An impressive range of perspectives were presented — the "long-term" view included those representing mid- and long-term planning, and research and development (R&D) work that is important to ensure the necessary work is being done now so facilities that will be needed in the coming decades have the supporting data, analyses, planning, and public input necessary to succeed. Other topics presented included policy and legal issues, cask vendor activities, decommissioning, and specific country and utility activities.

The short-term perspective includes work that utilities are doing every day in this one component of the fuel cycle to ensure that nuclear reactors continue to generate reliable electricity and make enough money doing it to keep those reactors operating until the end of their licensed life, and that the spent fuel is stored safely beyond the licensed life. As with the long-term perspective, these activities also require years of detailed planning to be successful, but planning for managing spent fuel at a utility or reactor level has a definite end point when planning meets operations to keep reactors operating. On this level, the planning absolutely cannot be delayed for decades.

A separate but essential component of spent fuel management is the independent regulator that oversees and ensures the safe operation of nuclear plants, including managing the spent fuel, and which also works to ensure that appropriate regulatory requirements are clearly and consistently communicated and met.

Key conference takeaways from the "long-term" perspective and who said them are as follows:

- The House of Representatives is willing to compromise on spent fuel management policy, but the overriding mentality is to follow the current law rather than starting over (U.S. Rep. Mark Meadows, R-NC).

- Neither the U.S. Department of Energy (DOE) nor the president of the United States intends to propose any legislation that would provide the authorization needed to advance the Administration's January 2013 "Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste" (Jeff Williams, DOE).
- U.S. Nuclear Regulatory Commission (NRC) staff is planning to complete the Yucca Mountain Safety Evaluation Report (SER) by January 2015 (Michael Weber, NRC).
- Waste Confidence update is on schedule to be completed in early fall 2014 (Michael Weber, NRC).
- Restarting the Yucca process would take decades less time and save "billions and billions and billions" of dollars compared to starting over with a brand new site (Chris Kouts, former director, DOE's Office of Civilian Radioactive Waste Management).
- The decision that Yucca Mountain was "unworkable" was made by U.S. President Obama and carried out by the U.S. Secretary of Energy with no studies or documentation to back the statement up (Kouts).

- Consent-based siting is very difficult to sustain over decades (various).
- Storage and transportation of spent nuclear fuel (SNF) — even high burnup SNF — is safe and the work the NRC and others are doing is to confirm and document that message (Mark Lombard, NRC, and Ken Sorensen, Sandia National Laboratories).
- Decommissioning nuclear power plants has a renewed focus with the early closure of five nuclear power plants (Larry Camper, NRC).
- In the next twenty years more than half of the reactors currently in operation worldwide are expected to be closed and primed for decommissioning (Jeff Hays, AREVA TN).
- Global collaboration is vitally important to tackle the unprecedented cleanup of the Fukushima Daiichi Nuclear Plant (Kenji Tateiwa, Tokyo Electric Power Company).

After brief opening remarks by Jeff England, who organized and chaired the seminar, Eric Knox, NIC chair, said to any policymakers who might be in attendance: "let's get on with it." Knox added that industry has shown it can rise to any occasion and meet any challenge as long as a decisive path forward is set.

Policy

Jeff Williams, director of DOE's Nuclear Fuels Storage and Transportation Planning (NFST), noted that DOE is working to advance its new strategy, which was released on January 11, 2013, by focusing on planning and R&D that can be done under current law (the *Nuclear Waste Policy Act*, NWPA). The strategy includes eight key components that are intended to finally resolve the backend of the nuclear fuel cycle after the administration scuttled Yucca Mountain, but some of the components require congressional action before site-specific work can be done. The strategy incorporates recommendations of the Blue Ribbon Commission (BRC) on America's Nuclear Future, which are now two years old, and which used words like "expeditiously" and "promptly" to convey the importance and sense of urgency that should be understood about this important issue of spent fuel management.

Williams mentioned the *Nuclear Waste Administration Act of 2013* (S.1240) that U.S. Senator Ron Wyden (D-Ore.) introduced in June 2013. According to Williams, DOE supports this bill as a way to advance the department's new strategy. Williams hopes that the Senate will have an opportunity to consider this bill "in the not too distant future," as it would provide a "vital framework to move forward." If a similar bill is introduced in the U.S. House, however, the future of that legislation "will become more cloudy," since the House is much stronger in its support for Yucca Mountain, and much less inclined to simply scrap Yucca Mountain and start over. In response to a question, Williams confirmed that neither DOE nor the president has put forward any legislation to advance the strategy or the BRC recommendations, but both are relying on proposals submitted by Congress. Not many participants were optimistic that any legislation that deals with the thorny issue of nuclear waste will get passed in 2014 because of the mid-term elections, so the expectation is that the status quo will reign for yet another year.

Williams explained that DOE's used fuel disposition mission has two components — R&D and transportation planning. In the R&D area, DOE received "substantial input" from CB&I, NAC International, Holtec International, and AREVA TN last year on standardized canisters and storage systems. DOE is evaluating the pros and cons of standardization, has completed a database of siting efforts in the United States and abroad, and has started to gather information to inform the department on how a consent-based process is understood by the public. R&D work is also being conducted to better understand potential degradation mechanisms in dry storage systems in the long term, since extended storage is becoming the default long-term management option. Williams referenced the work being done with the Electric Power Research Institute (EPRI) and others on this project. DOE issued the draft test plan for this project for public comment, and met last week with the partners to finalize the plan, which was released on February 27, 2014.

Williams noted that DOE is collaborating with its international peers and partners on repository development work. Since the Unites States does not know where a deep geological repository will be sited using a consent-based process, Williams observed that perhaps the U.S. will be able to benefit from research in other countries that have been operating an underground laboratory, for example.

Ongoing DOE work includes revisiting a study about whether defense nuclear waste and spent fuel from commercial nuclear power plants should be "comingled" in the same repository. In 1985 a study was conducted that led to the decision that one repository should be constructed for both civilian and defense waste. The BRC, however, suggested the issue be reevaluated and DOE has thus initiated an analysis of the pros and cons of comingling this waste in a single repository. The decision ultimately will be made by the president.

Williams also said DOE is working to complete a supplemental environmental impact statement (EIS) on groundwater the NRC had asked it to complete for the Yucca Mountain SER. (DOE has since decided not to complete that supplement, however.)

Michael Weber, NRC's deputy executive director for operations, offered a high-level overview of activities related to the Yucca Mountain SER, Waste Confidence, and improvement initiatives at the agency. Weber said the NRC staff is planning to complete the Yucca Mountain SER by January 2015 using previous work. The agency is reassembling a review team for that effort, and is coordinating work on the EIS supplement with DOE. The NRC is also loading documents into ADAMS; references to the SER will be publicly available, Weber said.

As to Waste Confidence, Weber said that as of December 30, 2013, the NRC had received 2,960 comments on the draft generic environmental impact statement (GEIS) and proposed rule. The agency held thirteen public meetings on the GEIS and rule, in which 1,400 people participated. More than 33,600 comments were submitted, 850 of which were unique (the overwhelming majority were form letters submitted by members of organizations such as Sierra Club). Themes of comments included: generic versus site-specific consideration; expedited transfer from pools to dry casks; long-term storage of high-burnup fuel; uncertainty about a repository; and durability of institutional controls.

In a session that could be characterized as a "what if Yucca had not been abandoned" where presenters commiserated on the costs — both tangible and intangible — of the Yucca termination, Chris Kouts, former director of DOE's Office of Civilian Radioactive Waste Management (OCRWM), was scathing in his remarks about the decision to desert the program. Kouts first noted that OCRWM was illegally dissolved when DOE abandoned the Yucca Mountain program, then after reviewing the time and money spent on developing the site, he emphasized that the bottom line is that the United States lost a repository site, "which you cannot put a price tag on." Kouts was not suggesting that the United States build a repository at the Yucca site, but did suggest that it should be taken through the licensing process so the country would know if the site could potentially host spent fuel and HLW.

Legal Perspective

Eighty breach of contract lawsuits have been filed against the United States because the government has yet to meet its statutory duty to remove spent fuel from reactor sites. According to Jay Silberg of Pillsbury Winthrop Shaw Pittman, LLC, thirty-three of those lawsuits have been settled, with $2.7 billion paid to utilities thus far, and an additional $991 million paid to utilities as a result of twenty-six final judgments of these suits. DOE estimates that additional payments totaling $21.4 billion will be paid to utilities — if DOE starts to perform by 2021, which is the year DOE's 2013 Strategy identifies as having a pilot interim storage facility operating. That strategy calls for a repository to be operating in 2048 — the golden anniversary of the first date DOE was supposed to start moving spent fuel from reactor sites. Considering that enabling legislation has yet to be passed, the 2021 date is in jeopardy.

Judgments in the Court of Federal Claims as a result of the damages lawsuits are continuing, Silberg said. On November 13, 2013, the "three Yankees" received a total of $235 million in damages, and other suits are in progress, since utilities can only file for damages incurred and therefore must file new suits every few years for new damages as they accrue. Silberg said most utilities are satisfied with the settlement process, so those are continuing. Post-2009 settlements expired December 31, 2013, but hopefully will be extended.

Silberg pointed out that DOE has requested no funding, and has introduced no legislation to advance its new strategy, even though the strategy document recognizes the need for both. The Senate introduced a bill (S.1240) last year that would advance the goals set forth in the strategy, but the bill is silent on Yucca Mountain; by contrast, the House of Representatives continues to believe the Yucca Mountain licensing process should be continued.

Silberg called the nuclear waste fee the "Goldilocks" fee since it must be determined to be neither too big nor too small. In 2009 the National Association of Regulatory Utility Commissioners (NARUC) and the Nuclear Energy Institute (NEI) sought relief from this fee in federal court because DOE no longer has a program in place by which to judge how much utilities should be assessed to pay for the (now non-existent) program. To date, utilities have paid over $30 billion into the Nuclear Waste Fund — a fund that increases by $1.5 billion (well over any amount ever appropriated by Congress) each year from interest alone. The court ruled in November 2013 that DOE's latest fee assessment was once again legally inadequate, and said further that DOE's position was "obviously disingenuous," "pie in the sky," "based on assumptions directly contrary to law," and "the old razzle dazzle." The court ordered DOE to propose reducing that fee to zero until either DOE complies with current law (proceed with Yucca Mountain) or until "Congress adopts an alternative waste management plan." DOE filed a Petition for Rehearing, in which it argued that the DC Circuit decision:

- Inconsistently prohibited use of Yucca Mountain costs and non-Yucca Mountain costs;
- Is inconsistent with the Aiken County decision requiring the NRC to restart Yucca Mountain licensing;
- Should have remanded to give DOE another bite at the apple.

A rehearing would require a majority of active judges, and NARUC/NEI may not respond to the request unless asked to do so by the court. (Update: on March 17, 2014, the full Court rejected DOE's Petition for a Rehearing.)

Early in January 2014, the DOE very reluctantly submitted a proposal to zero out the fee. In the letter to Congress DOE argued that the proposal it was ordered to submit is inconsistent with the *Nuclear Waste Policy Act*. The proposal will become effective after ninety days of Congress' "continuous session," unless Congress enacts contrary legislation. DOE also has filed for a rehearing by the full appeals court.

Looking to the future, Silberg noted that DOE's new strategy needs legislation to proceed with many of its components — consent-based siting, funding reform, establishment of a new organization, and to study a site other than Yucca Mountain. As does the old strategy (codified in the NWPA), the new strategy includes linking an interim storage facility with a repository. Linkage in the NWPA "doomed" a similar idea in the 1980s – the Monitored Retrievable Storage (MRS) facility. Furthermore, Silberg contended that legislated linkage is inconsistent with consent-based siting because if a storage site has consent notwithstanding the status of a repository, then why should repository status hold up developing a storage facility? Silberg noted that consent-based siting was tried before, and he reminded the audience of the duties of the Nuclear Waste Negotiator.

For the new strategy, consent has not yet been defined, including whose consent is needed and how long might consent last for a multi-decade project. What happens when the "next Senator Reid" comes along and derails a site that has been identified and in which billions of dollars have been invested, Silberg asked. Which comes first — the geology or the consent? Senate bill S.1240, on which DOE rests its hope for gaining congressional authorization to move forward with concrete activities other than R&D, requires a consultation agreement with the identified community before site characterization can begin, then a consent agreement after site suitability is determined. How many terms of office will this take? Silberg wondered.

For interim storage, Silberg suggested that a community should get approval from current elected officials, the governor, and leadership of the political party that is not in power, with a "wish list" on which they can all agree, then submit that package to Congress, which can then accept or deny it.

The U.S. Spent Fuel Dilemma

Nigel Mote, executive director of the U.S. Nuclear Waste Technical Review Board (NWTRB), pointed out some commonalities among nuclear countries with regard to spent fuel management. The disposal of spent fuel and/or high-level radioactive waste (HLW) in a deep geologic repository is an internationally accepted concept, with most nuclear countries planning to develop a repository at some point. Many countries, most notably the United States, have had resets in repository programs; not a single ton of spent fuel has been disposed of to date, and no repository is even licensed in the world. Some countries do reprocess spent fuel, but reprocessing is not a final solution, as a repository is still needed for the waste resulting from that process. Long-term storage of spent fuel and/or HLW is today's reality.

Progress is possible, Mote noted, with Sweden, Finland, and France being the three countries closest to having an operational repository. Sweden and Finland both have submitted a license application to their respective regulators, in 2011 and 2012, respectively. Both countries will use the SKB/KBS-3 concept, with small spent fuel disposal canisters that will contain four PWR or nine BWR assemblies. France plans to submit a license application in 2014. Its facility will hold containers of vitrified HLW resulting from reprocessing, and will include PWR spent mixed-oxide (MOX) fuel assemblies as well. Belgium, Canada, China, Germany, Japan, Korea, Russia, Spain, Switzerland, and the United Kingdom are all in various stages of siting and repository development.

Sweden, Finland, and France all used a consent-based site selection process. The success so far in Sweden and Finland using this process was highly touted in the United States by the Blue Ribbon Commission (BRC) on America's Future as a key to their successful siting efforts. These three countries, however, all have single-purpose implementers; all have long-term, multi-year, assured budgets; all have stable political support; all have high staff retention rates; and all have focused on demonstrating long-term safety as opposed to just meeting regulatory requirements. All have also focused on establishing and maintaining public acceptance.

None of the above factors, however, guarantees success, Mote pointed out, with both Sweden and France having gone through an initial "reset" before realizing a successful siting effort.

The United States is in a complicated dilemma. Dry storage is widely used by now, with close to 1,900 dry storage systems currently deployed at commercial reactor sites, in addition to dry storage that is in use at DOE sites (according to data from UxC's *StoreFUEL* publication). By volume, about 65,000 MTU is in storage in the United States, approximately 20,000 of which is in dry storage. By the year 2020, about 3,000 dry storage systems are projected to be in use, and by the time a repository is operational approximately 12,000 large casks or 80,000 small ones could be in use to store the 150,000 MTU of spent fuel that has been discharged. DOE has proposed using smaller casks/canisters for permanent disposal, which would mean all the casks loaded to date and up until a repository is operational would have to be unloaded and then reloaded into the smaller systems. Or, since a repository has not yet been sited and designed, should it be sited with the requirement that the geology and design could accept the larger systems for direct disposal? The U.S. dilemma is that both repackaging and direct disposal have significant implications for spent fuel management, Mote noted.

Utilities are currently using large, high-capacity systems, some of which are not even designed for transportation, and most of which are not licensed for transportation even if the system is designed to be transported. Use of the high capacity systems is driven by the economics of the utilities, since there is no basis now for alternative strategies for utilities. A few years ago, utilities were willing to consider a smaller capacity transportation, aging, and disposal, or TAD, canister system that DOE intended to use at the Yucca Mountain facility, but the TAD systems never were licensed since DOE abandoned the Yucca Mountain site as an option.

In presenting the U.S. spent fuel "dilemma," Mote pointed out that repackaging spent fuel that is currently in large dry storage casks would mean more: facilities, fuel handling, dose, low-level radioactive waste, transportation operations, disposal packages, and emplacement operations. On the other hand, direct disposal would present a different set of problems, including handling and emplacement of large, heavy packages with a high heat load and a higher fissile content than would be present in the small packages. These factors could affect predicted long-term repository performance.

The NWTRB is planning to issue a report later this year on the implications of different canister designs.

Spent Fuel Management in Spain

David Garrido of Equipos Nucleares, S.A. (ENSA), provided a report on the present scenario of spent nuclear fuel in Spain and the strategy for handling spent fuel in the future. See his article beginning on page 60.

Utility Experience

Exelon's Zion Station is currently being decommissioned. A major project in the decommissioning effort is to move all the spent fuel from wet storage into dry storage. This fuel transfer project will be longest continuous dry storage campaign to date. It began in December 2013 when the first fuel assembly was loaded into an NAC International MAGNASTOR system one minute before midnight on December 18. About four weeks later, that first cask with thirty-seven assemblies in it was moved to the storage pad on January 9, 2014. The Zion Station was permanently shut down in January 1998, and was in SAFSTOR status until 2010 when decommissioning activities began. The two units share a common spent fuel pool, in which 2,226 spent fuel assemblies have been stored. All of these assemblies will be transferred into sixty-one casks in one continuous campaign that is expected to be complete at the end of this year. Cask loading operations are running twenty-four hours a day, seven days a week using several teams. An additional four casks will be used for greater-than-Class C (GTCC) waste.

Zion holds a general license for operation of its ISFSI. In September 2010, Zion*Solutions* (ZS), a subsidiary of Energy*Solution*s (ES), assumed the Part 50 license from Exelon for the purpose of decommissioning the plant — including transferring all the spent fuel assemblies to dry cask storage. ZS plans to transfer ownership of the ISFSI to Exelon as the registered user after decommissioning is complete.

Bill Szymczak, Nuclear Fuel specialist for ZS, described the project at last month's Spent Fuel Management seminar, sponsored by the Institute of Nuclear Materials Management. In 2012 and 2013, the site was busy preparing for this fuel transfer project. During this time segmentation of both reactor vessel internals was underway. Upcoming decommissioning milestones include:

- 2014 take the plant to "cold and dark" status;
- 2015 complete removal of contaminated equipment;
- 2016 complete the demolition of the turbine and support buildings;
- 2017 complete all major demolition;
- 2018-2019 complete site restoration and final status surveys;
- 2020 complete the entire project.

The Zion ISFSI has two pads, each of which is 148 feet x 68 feet. The site has sixty-one fuel and four GTCC vertical concrete casks (VCC) constructed on the site. These are the concrete storage overpacks into which the transportable storage canisters (TSC) are placed for long-term storage. As of the date of the presentation, twenty of thirty-one TSCs had been delivered, and seventeen of thirty damaged fuel TSCs had been delivered for a total of thirty-seven of the sixty-one TSCs that will be used for storing spent fuel being on site. In addition, all four of the GTCC TSCs have been delivered.

As a result of fuel inspection and repair campaigns, which took place from July 2011 until March 2012, and in June 2013, instrument tube tie rods (ITTRs) were installed in a total of 1,478 fuel assemblies that were susceptible to top nozzle guide tube intergranular stress corrosion cracking (IGSCC). Guide tube anchors (GTAs) were also installed in three fuel assemblies due to the top nozzle IGSCC issue. ITTRs and GTAs are considered approved contents for the MAGNASTOR system. Also based on the results of these campaigns, ninety-seven fuel assemblies were classified as damaged and will be packaged in damaged fuel cans (DFCs).

ZS gave special consideration to three groups of fuel assemblies — 201 assemblies were considered low burnup (high reactivity) assemblies that were in storage due to the premature shutdown of the plant. These assemblies are acceptable for storage but not for transportation due to criticality concerns, so each assembly will be loaded with an RCCA (control rod) inserted and in restricted locations. Thirty-seven assemblies were considered high burnup assemblies, as they had achieved a burnup of more than 45,000 MWd/MTU. As a precautionary measure, these assemblies will be placed into damaged fuel cans. The concern with high burnup assemblies is cladding embrittlement for transport. The third group of fuel assemblies that required special treatment is the damaged fuel assemblies. This group includes failed fuel, which was identified through records review, visual inspection, and sipping campaigns. The sipping campaign took place from February 2012 until March 2012, when 1,369 fuel assemblies were sipped. Sixty fuel assemblies were classified as damaged. Both the high burnup and the damaged fuel assemblies will be loaded into damaged fuel cans.

In addition to the fuel assemblies, non-fuel inserts hardware also will be stored in the cask systems, and all of these items are within the approved contents of the certification of compliance (CoC).

As at most sites, loading the first cask presented some challenges. One challenge was the extremely cold weather. Other challenges included a bent stainless steel neutron absorber retainer, a helium backfill fitting leak, and the fact that the first TSC had been used for dry runs and therefore had been submerged in the pool several times before loading, there was some water clarity issues and a bit of corrosion on the TSC basket.

Major work accomplished in 2013 included: construction of the ISFSI pad completed; fuel transfer preparations completed; began fuel transfer operations; Unit 2 reactor internals segmentation began; began removing equipment from the Auxiliary building; Class B & C waste were shipped to Waste Control Specialists in Texas in two shipments; and low-level waste was shipped in forty-five rail cars to the *EnergySolutions* LLW disposal facility in Clive, Utah, USA.

Szymczak explained that a project such as this requires making multiple interconnected storage decisions, first at the fuel assembly level, then at the cask level, and finally at the ISFSI pad level. These decisions rely on a large body of information, including: storage regulatory requirements of both Part

Table 1. NAC MAGNASTOR/MAGNATRAN at Zion

	Qty
Transportable storage canisters (TSCs) 37 undamaged PWR fuel assemblies max	31
Transportable storage canisters -- damaged fuel Up to four damaged PWR fuel assemblies in damaged fuel cans plus 33 undamaged PWR fuel assemblies	30
Transportable storage canisters for GTCC waste	4
Total number of TSCs	65
Total number of storage cells (61x37)	2,257
Vertical Concrete Casks (VCCs)	65
ISFSI PAD CAPACITY	Qty
North Pad (VCCs/TSCs)	36
South Pad (VCCs/TSCs)	36
Total	72

72 and the cask CoC; transportation regulatory requirements of both Part 71 and the transportation cask CoC; offsite dose calculations; fuel classification and characterization results; cask modeling requirements (by using EPRI CASKLOADER); fuel pad loading and alternative assembly strategy; and site-specific requirements. At Zion, the fuel loading plan must ensure that requirements of both storage and transportation are met.

Szymczak described the factors that must be considered during the fuel load planning process, which include meeting offsite dose calculations and the criticality requirements of both the storage and transportation CoCs. An alternate assembly strategy must be developed in the unlikely event that a fuel assembly is damaged during the loading process. Zion reserves two spare canisters to use in such a circumstance. Any fuel assemblies damaged during the loading process will also be put into damaged fuel cans and loaded into an alternate canister, but all assemblies must eventually be loaded. ZS developed sixty-one individual TSC loading plans for each cask to be loaded at the site, optimizing the fuel loading plan to minimize offsite dose.

The 30th INMM Spent Fuel Seminar will be January 12-14, 2015, at the Crystal Gateway Marriott Hotel in Arlington, Virginia, USA. Information will be available on the INMM website in November 2014.

Carlyn Greene joined the Ux Consulting Company, LLC (UxC), in May 2008 and is currently executive director, Backend Publications. Greene has more than thirty years of nuclear industry experience, including six years with Washington Nuclear Corporation and nearly twenty years at NAC International. Prior to joining UxC, Greene was associate editor of SpentFUEL and StoreFUEL for Washington Nuclear Corporation, where she also assisted with consulting studies related to spent fuel storage, decommissioning, and nuclear fuel costs. With *UxC's purchase of these two backend newsletters, Greene has assumed the managing editor responsibilities for those products, as well as assisting with other UxC projects. From 1980 to 1999, she was employed at NAC International, where she assumed various responsibilities, including Supervisor of Data Analysis for the Fuel-Trac database, and research analyst for the uranium and enrichment markets. She also assisted with the Uranium Price Information System, the Uranium Supply Analysis (USA) System, and the Worldwide U3O8 Producer Profiles.*

Greene graduated from Mercer University in Macon, Georgia, USA with a bachelor of arts degree in English and communication in 1978. She is a member of the American Nuclear Society, Women in Nuclear, and the Institute of Nuclear Materials Management.

Spanish Scenario for Spent Fuel in Spain

David Garrido Quevedo
Equipos Nucleares, S.A. (ENSA), Cantabria, Spain

Abstract

The spent nuclear fuel management strategy has been an important issue of discussion in the nuclear community for several years. Its importance is directly related to political decisions, and governments all around the world are currently planning different strategies considering the technical, economical, and safety factors as part of their decisions. The international economic crisis together with the consequences of recent nuclear accidents have encouraged governments and nuclear stakeholders to plan and work on feasible alternatives for the spent nuclear fuel management strategies.

The purpose of this paper is to show, in particular, the Spanish scenario for spent fuel management and the decisions being made in Spain. A brief introduction of the current nuclear situation in Spain is followed by an overview of the stakeholders on the spent fuel management and the actual spent fuel scenario, describing the inventory and the estimation of the total amount of spent fuel over a total period of forty years of nuclear power plant operation. The current spent fuel scenario will also go through and describe the different solutions taken in the past and nowadays for spent nuclear fuel dry storage in some of the Spanish nuclear power plants. But this is almost like in any other country, so, *what's different in Spain?* The answer is the strategy recently decided upon and approved for the near future, called *ATC* for "*Almacén Temporal Centralizado,*" the Centralized or Consolidated Interim Storage Facility. A description of the ATC siting process is provided, as well as the design basis, the criteria used for the selected technology, similar international references, and, finally, several issues to be considered on this strategy concerning the fuel burnup, routing infrastructure, and spent fuel integrity and operation. Because the ATC solution is a temporary solution (100 years at best), this paper concludes with a reflection or consideration being made — *what's next?* It cannot be forgotten that other alternatives, such as Deep Geological Disposal, Reprocessing and Recycling, Transmutation, etc., are still there, fighting for a place and an opportunity for the future spent fuel management.

Introduction: Nuclear Energy in Spain

The original nuclear infrastructure in Spain consists of ten nuclear power reactors. Eight of them are in operation at six sites and the other two have been permanently shut down. (See Table 1.) In 1992 the LILW & VLLW disposal facility of *El Cabril*, started its operation. (See Figure 1.)

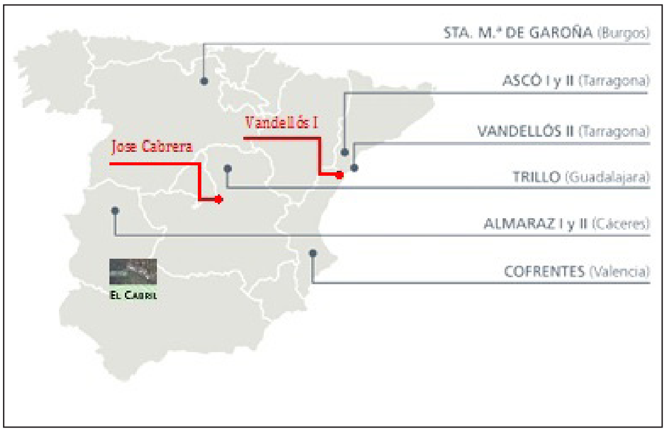
The design of the Spanish nuclear reactors is mostly pressurized water reactor (PWR). Only two reactors are boiling water reactors (BWR) and one of the dismantled reactors was based on the gas-cooled reactor (GCR) technology. Table 1 lists the Spanish nuclear reactors detailed information, such as Type, Power, Initial Startup, Authorization, Extension and current operating status.

Table 1. Spanish nuclear reactors, general information

NPP	Type	MW	Initial Startup	Authorization	Extension Approval	Status
Almaraz 1	PWR	1.049	1981	2010	10	Operating
Almaraz 2	PWR	1.044	1983	2010	10	Operating
Ascó 1	PWR	1.033	1983	2011	10	Operating
Ascó 2	PWR	1.035	1985	2011	10	Operating
Cofrentes	BWR	1.102	1984	2011	10	Operating
José Cabrera	PWR	150	1969	2006	-	Decommissioning
Santa María de Garoña	BWR	466	1971	2009	4+6	Stand-by
Trillo 1	PWR	1.066	1988	2004	10	Operating
Vandellós 1	GCR	480	1972	1989	-	Dismantled/ Latency
Vandellós 2	PWR	1.087	1987	2010	10	Operating

Two of the three oldest reactors, Jose Cabrera and Vandellós 1 are now in different phases of decommissioning and dismantling (D&D). The third one, Santa María de Garoña, a BWR design plant is on "stand-by," waiting for a final decision. Recent nuclear taxes, strong investments due to the post

Figure 1. Nuclear reactors and disposal facilities in Spain



Fukushima-Daiichi consequences, and the short remaining operating period have already created a tense situation between the utility and the government, resulting in a "stand-by" situation where the plant is currently shut down.

Using the data from 2013,[1] nuclear power in Spain represented 7.7 percent of the installed power (7.8 GWe), representing 21 percent of all the energy production. Figure 2a shows the installed power by different energy sources (left) and 2b the corresponding energy demand coverage (right). It is important to notice the differences in these parameters between the nuclear energy and, for example, the wind energy, that represented 22.2 percent of the installed energy but only accounted for 21.1 percent of energy production.

It is always important to know, for a better understanding of the spent fuel management who are the stakeholders involved in these activities. In Spain, there are four main stakeholders dealing with spent fuel management, as follows:

- The Ministry of Industry, Energy, and Tourism (MINETUR), is part of the Spanish government. Among its responsibilities are establishing the policies for radioactive waste, decommissioning, and spent fuel management. This ministry also grants the licenses of all nuclear installations and transport/storage casks.
- The Nuclear Safety Council (CSN), is independent from the government and provides nuclear safety and radiological protection guidelines based on the preparation and issuance of safety regulations and guidances. It is responsible for the evaluation of the design safety analysis reports and to generate the safety evaluation reports prior to the license. Its decisions are binding.
- Enresa is the public company in charge of the safe management, storage, and disposal of the radioactive wastes produced in Spain. Enresa is also responsible for the dismantling of nuclear power plants when their service lifetime has come to an end and for the environmental restoration of disused uranium mines and facilities. In addition to undertaking the technical aspects of radioactive waste management, Enresa manages and administers the economic resources obtained for the financing of the functions for which it was set up. As established by law, the costs of activities deriving from radioactive waste management shall be financed by the waste producers. Figure 3, on next page, shows the organization chart and the relationship between these three organizations.
- Nuclear power plants (NPP)/utilities and cask vendors are also part of this group. Utilities and plants are responsible for operational activities related to spent fuel in the Independent Spent Fuel Storage Installation (ISFSI), during the storage period. They are also responsible to provide and deliver the spent fuel and waste packages in accordance with the conditions previously agreed with Enresa. As waste management activities generate cost, according to the General Radioactive Waste Plan, these costs shall be

Figure 2a. Installed power data from 2013

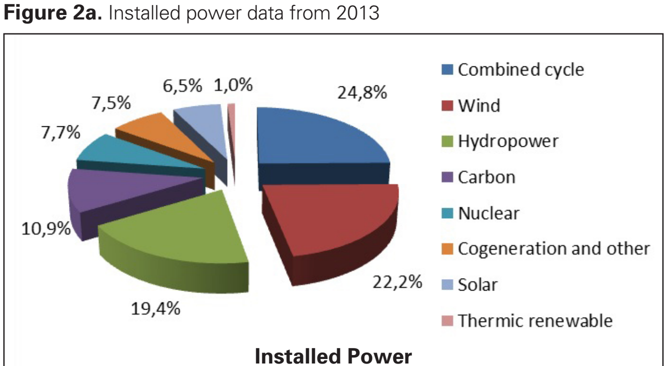


Figure 2b. Energy demand coverage data from 2013

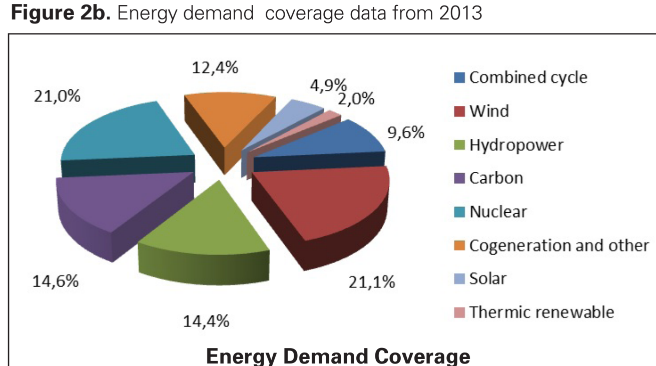
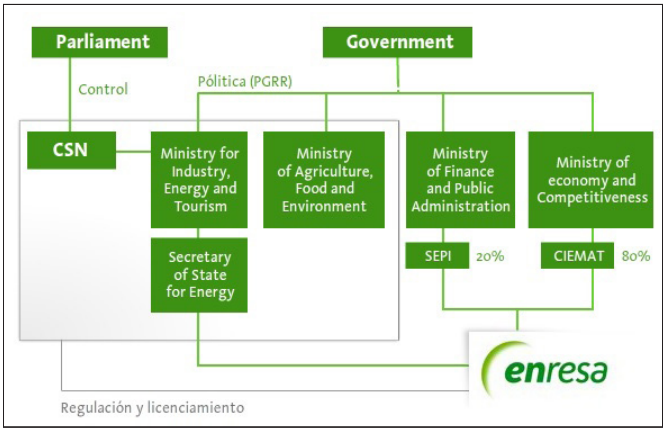


Figure 3. Related organizations in the SF management[2]



covered by the utilities (waste producers) through fees. Cask vendors, such as Equipos Nucleares, S.A (ENSA), are responsible for the design, licensing, fabrication, inspection, and delivery of the spent fuel dry storage system. Further to these activities, ENSA is directly involved with the cask loading activities, using its own resources or helping the plants during the cask loading operations.

The Spanish Current Spent Fuel Scenario

A total of 4,600 tU of spent nuclear fuel are stored in the different Spanish nuclear power plants. Most of them are stored in the spent fuel pools. Three ISFSIs are in operation at the moment, located at Trillo NPP, Jose Cabrera NPP (in decommissioning) and the Ascó NPP. A fourth ISFSI is currently in the licensing and construction phase at Santa María de Garoña plant. The best estimation of the total amount of spent fuel in Spain, assuming each reactor operates for forty years, is around 20,000 fuel elements, equivalent to 6,700 tU. This number is useful for further decisions.

As indicated before, there are currently three ISFSIs in operation in Spain and one more is on the way. The picture below (Figure 4) shows the location of these ISFSIs, as well as the future centralized interim storage facility (ATC).

The following paragraphs describe in more detail each ISFSI and the technology selected for spent fuel dry storage at each site.

The first nuclear power plant in Spain to require dry storage was Trillo NPP. Due to the spent fuel pool dimensions (a small pool inside the reactor building), and based on the plant outage strategy, the spent fuel pool did not allow for any more open locations. To cover the needs of the plant, ENSA designed a dual-purpose metal cask, ENSA-DPT (see Figure 5). The ENSA-DPT is a metal cask based on a multiwall structure of stainless steel-lead stainless steel. The closure system consists of a double lid, bolted and metallic seals in each lid to assure leak tightness. As a confinement safety measure, the interlid region is pressurized and continuously monitored. The total loading

Figure 4. Location of the ISFSIs in Spain and the future ATC or centralized interim storage facility

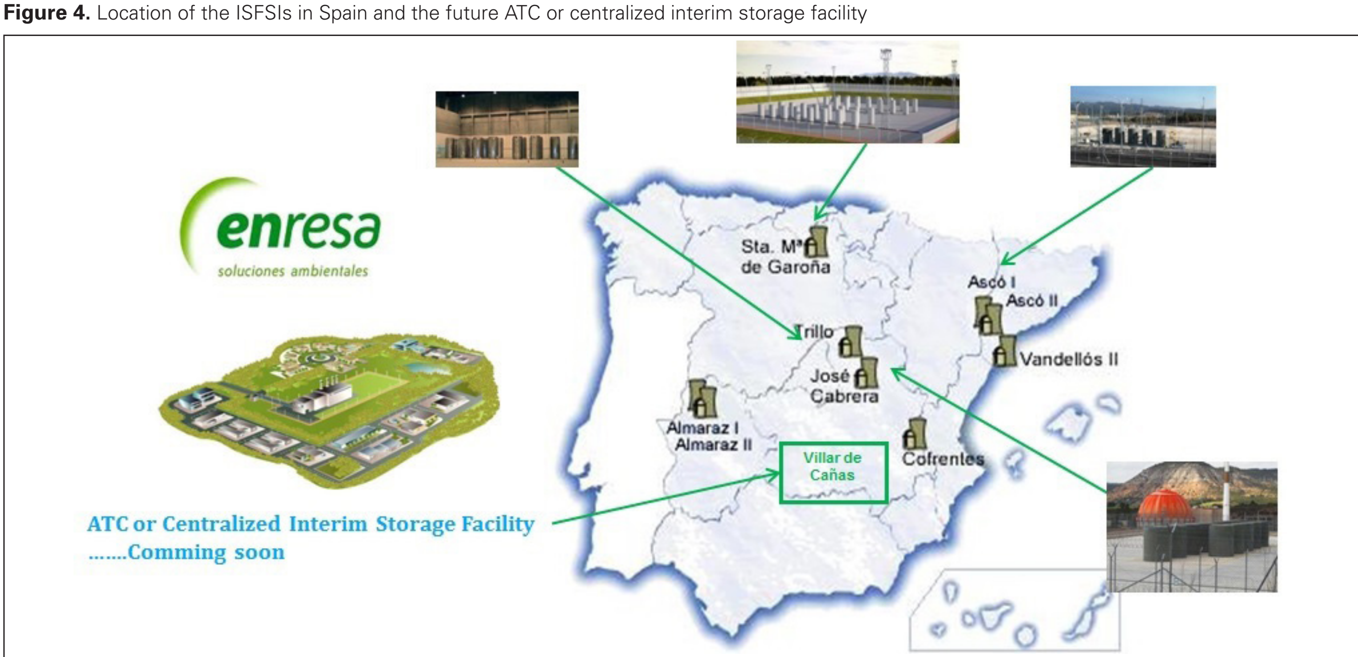


Figure 5. ENSA-DPT dual purpose metal cask

Figure 6. Trillo ISFSI and ENSA-DPT casks inside the building

capacity of the ENSA-DPT is up to 21 PWR Siemens KWU 16x16-20 fuel type assemblies, with a maximum burnup of 49 GWd/tU. Although ENSA was the designer, in this case the licensee was Enresa. This used to be the standard procedure in the past. The technology selected for the Trillo ISFSI was a concrete building with air inlets and outlets, and a capacity for at least 80 ENSA-DPT metal casks (see Figure 6). To date, a total of twenty-five ENSA-DPT casks have been successfully loaded in Trillo (the first ENSA-DPT cask was loaded in 2002).

José Cabrera NPP became the second nuclear power plant to require dry storage after it was permanently shut down in 2006. The selected technology for dry storage of all the spent fuel was the HI-STORM system from Holtec International. This dry storage system consists of a concrete overpack with a stainless steel welded canister inside (see Figure 7). The loading capacity of each canister is up to thirty-two PWR 14x14 fuel assemblies (HIPAR and LOLOPAR types). The licensing process followed for the HI-STORM was similar to the ENSA-DPT, the licensee being Enresa. The ISFSI at this site is an open concrete pad with a capacity for 12 HI-STORM systems (see Figure 8). The site has also been licensed to store Greater-Than-Class C (GTCC) waste safely in the HI-SAFE Holtec technology.

The third plant to require dry storage was Ascó NPP. In this case, the spent fuel pool dimension did not allow for additional free locations. As in José Cabrera, the HI-STORM technology was selected. Ascó's ISFSI consists of two open concrete pads (see Figure 9), each with a capacity of sixteen HI-STORM 100 storage systems. Each canister can store up to thirty-two PWR Westinghouse 17x17 fuel type assemblies. Enresa is also the spent fuel storage system licensee.

Due to similar reasons, the spent fuel pool at Santa María de Garoña NPP will not be able to accommodate additional

Figure 7. Concrete modular system

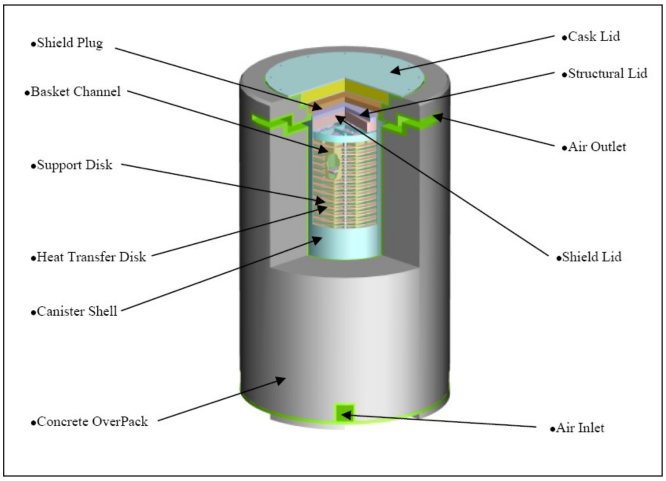
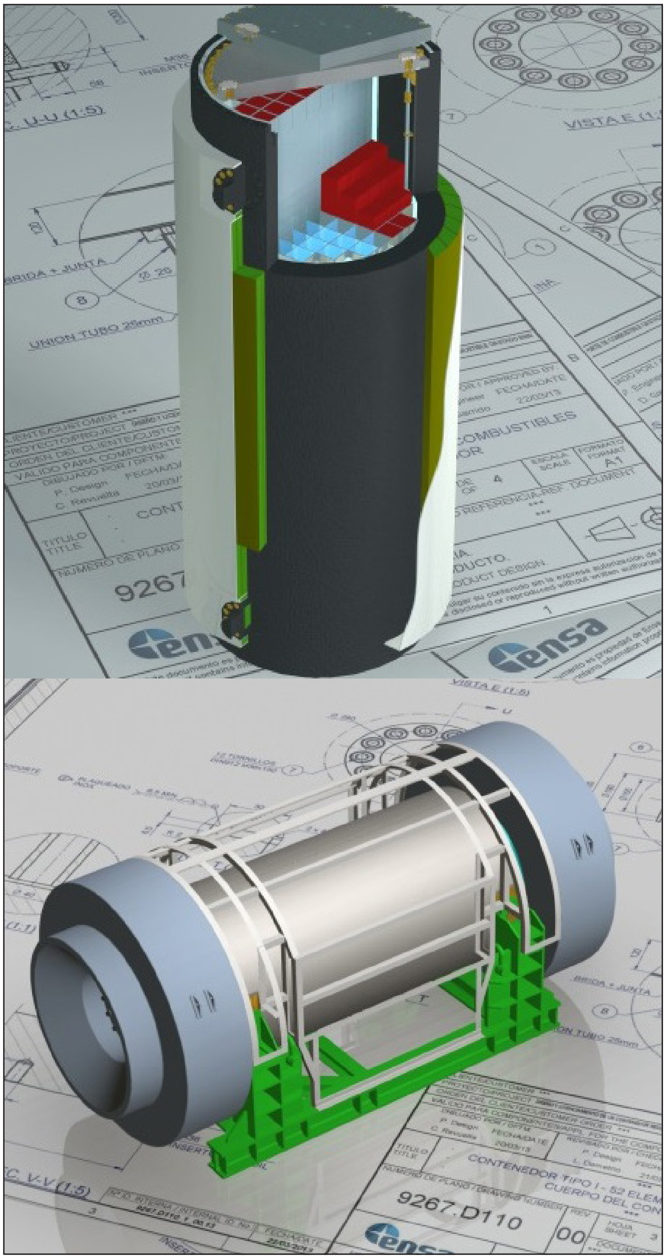


Figure 8. José Cabrera ISFSI and HI-STORM 100Z in the concrete pad

Figure 9. Ascó ISFSI and HI-STORM 100 in the concrete pad

spent fuel assemblies while meeting the capacity safety requirements and outage strategy. This situation makes Santa María de Garoña the fourth plant to require dry storage. ENSA's newest design technology, ENUN 52B, was selected to accommodate a fixed number of fuel assemblies in a first phase of loading campaigns. The ENUN 52B (see Figure 10) is a dual purpose (storage and transport) metal cask based on a monolithic carbon steel forging. The closure system consists of a double lid, bolted and metallic seals in each lid to assure leak tightness. As a confinement safety measure, the interlid region is pressurized and continuously monitored. The total loading capacity of the ENUN 52B is up to fifty-two BWR GE-6/7 fuel type assemblies. The ENUN 52B was designed to meet the Santa María de Garoña site-specific requirements, with several limitations, such as crane capacity (less than 75 t) and loading pit dimension, together with trying to optimize the loading capacity as much as possible. The licensing process scenario was modified for the ENUN 52B, being ENSA the licensee instead of Enresa. The license is currently under evaluation by

Figure 10. ENSA ENUN 52B dual purpose metal cask storage (top) and transport (bottom) configuration



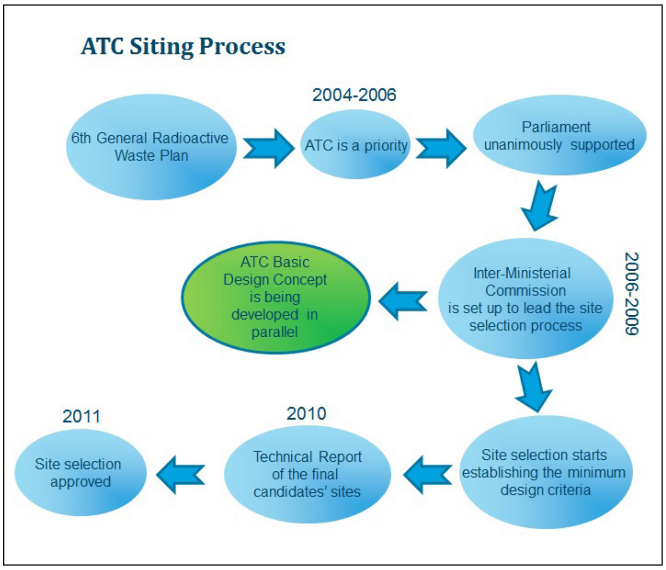
the Spanish Nuclear Safety Council (CSN) and expected to be approved within the next few months (summer 2014). The ISFSI at Santa María de Garoña consists of two open concrete pads (see Figure 11 in following page), each with a capacity of 16 ENUN 52B metal casks. The first loading campaign is expected to begin by mid-2015, but uncertainties due to the plant's current situation (stand-by) could modify the schedule.

Figure 11. Santa María de Garoña ISFSI and ENUN 52B in the concrete pad (artist views)

Spent Fuel Strategy in Spain for the Near Future

Spent fuel management strategy in Spain, as in many countries, has been an issue for several years. In 2004, as a result of the resolutions of the Congressional Commission for Industry, the government was urged to create a new General Radioactive Waste Plan (6th). This new plan includes, after the evaluation of different options, the start-up of a centralized temporary storage facility (called in Spanish ATC or almacén temporal centralizado) for the spent fuel and high-level waste generated in Spain and the dismantling of the nuclear power plants that reach the end of their service lifetimes. It is important to notice that deep geological disposal was preferred, but a couple of main issues, such as the uncertainties from the technical and operational point of view and social implications, turn the decision to the second best option for the country, the ATC. The ATC project was established in the 6th General Radioactive Waste Plan as "high priority," so the engine started to move. Between 2004 and 2006, several activities around the ATC project were performed and one of the most important was that the parliament "unanimously" supported the project. The process, which adheres to the directives of the European COWAM program, was governed by the principles of transparency and voluntary participation. The COWAM Spain project included the participation of representatives from town councils, autonomous communities, universities, professional associations, institutions, and organizations such as the Nuclear Safety Council and Enresa. In 2006, the government approved the setting up of an Inter-Ministerial Commission to establish the criteria to be met by the final site for the ATC facility. Site

Figure 12. ATC or centralized interim storage facility siting process



selection was carried out in the same way as in other countries that already have this technology in operation. The process for the selection of the site for the ATC facility covered: a) public information, b) call for proposals in the Official State Gazette, c) submittal of candidatures, d) selection of candidates, and e) designation by the Spanish government. This whole process took around three years (2006-2009). Later, in 2010 the technical report of the final candidates' site was released, to finally obtain the site selection approval by 2011. A preliminary estimation indicates that the ATC will be in operation around 2017. A flowchart of the ATC siting process is provided in Figure 12.

The ATC design is based on a vault system (see Figure 13) for both spent fuel and vitrified high level waste. A concrete building has been also considered for medium level waste. This concept will safely store and temporarily solve the spent fuel and other wastes storage problems for at least sixty years, with the potential to go up to 100 years. The selected technology criteria were based on three main topics: a) design, b) cost, and c) strategy. The design provides a multiple confinement barrier, cooling by natural draft and a very low dose rates (ALARA principle). The cost is reasonable, due to its configuration, based on a compact and modular design and low operational costs. This facility is absolutely independent of any management stages, long-term life design, and flexible to adopt any kind of modification.

There are several international references in relation to centralized interim storage. Some of them are in France (La Hague, Marcoule, and Cascad), Holland (Habog), the United States (Fort St. Vrain), and Hungary (Packs). Pictures of these facilities are shown in Figure 14.

Several issues came up and need to be considered in this strategy. Transportation of both low and high-burnup fuel from the nuclear power plants to the ATC facility is required, so different fuel loading combinations should apply. Because of this, the fleet of transport casks shall cover the whole Spanish spent fuel inventory. Continuing with the transportation topic, a detailed study on routing infrastructure was performed. Results show that several limitations were found in the case of railroad transportation. Therefore, road transportation was considered the most feasible mode of transport. Concerns directly related to spent fuel are nowadays in the hopper, and are basically the same in all nuclear countries with spent fuel transportation in their strategy. "*What, everyone is asking, will be the fuel integrity after several years of storage prior to transportation during Normal Conditions of Transport?*" In the Spanish scenario, the maximum storage estimated time before the first shipment is twenty years for low-burnup fuel and around ten years for high-burnup fuel. So are we ready for safe transport of especially high-burnup fuel? The answer is still up in the air and several international R&D programs (i.e., ESCP) are trying to provide evidence to confirm that the answer is yes. Another concern is related to those spent fuels stored in welded canisters. In this case, the welded canister will have to be opened to transfer the spent fuel into the ATC standard canister. This operation shall be performed inside a hot dry cell, where undesirable weld removal shall be required.

What's Next?

As indicated before, the ATC solution is a temporary solution, designed for 100 years but estimated to operate sixty years according to the 6th General Radioactive Waste Plan. For this reason, Spain is actively involved in several national and international research and development programs to find better solutions to nuclear waste in the future, i.e., Deep Geological Disposal, Reprocessing and Recycling, or even those that seem to be far off, such as Transmutation. Meanwhile, the ATC is gaining time on trends and technological and social progress before making the final decision.

Figure 13. ATC Conceptual Design based on a vault system

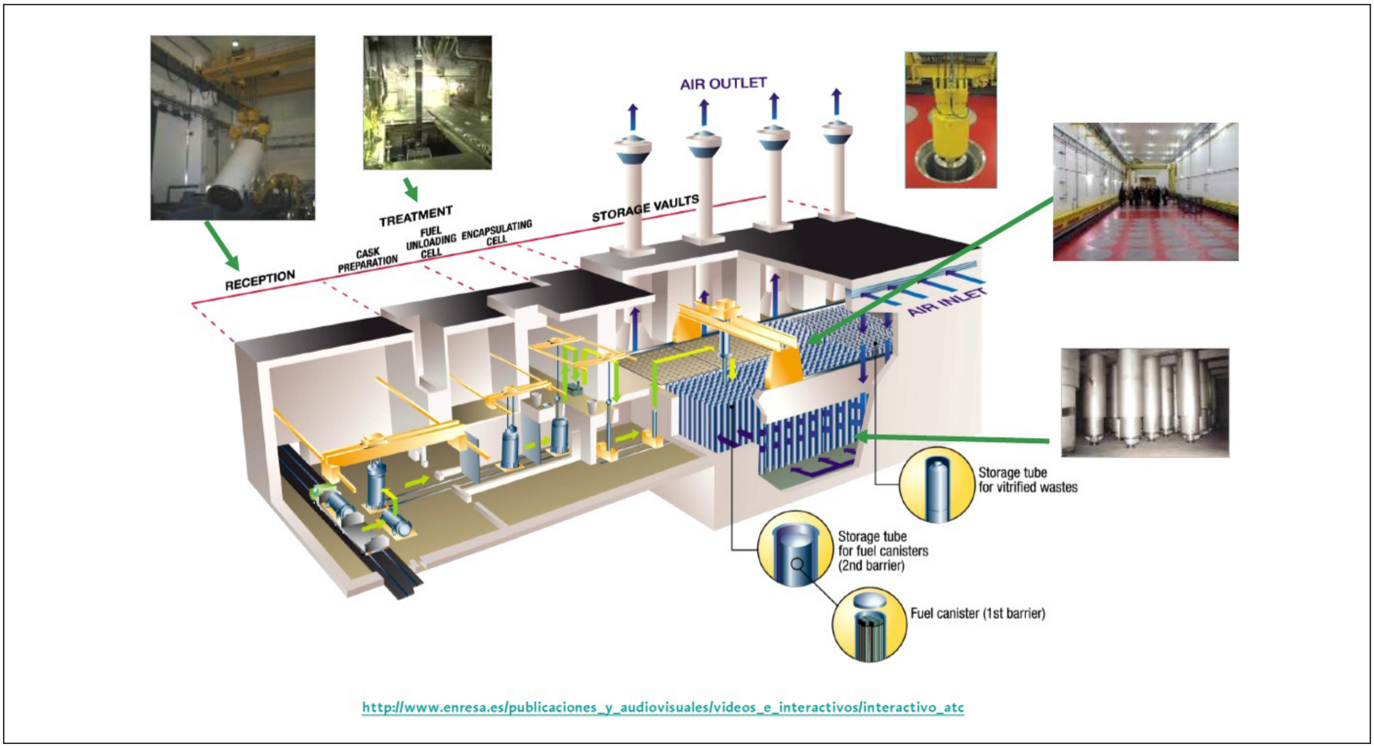
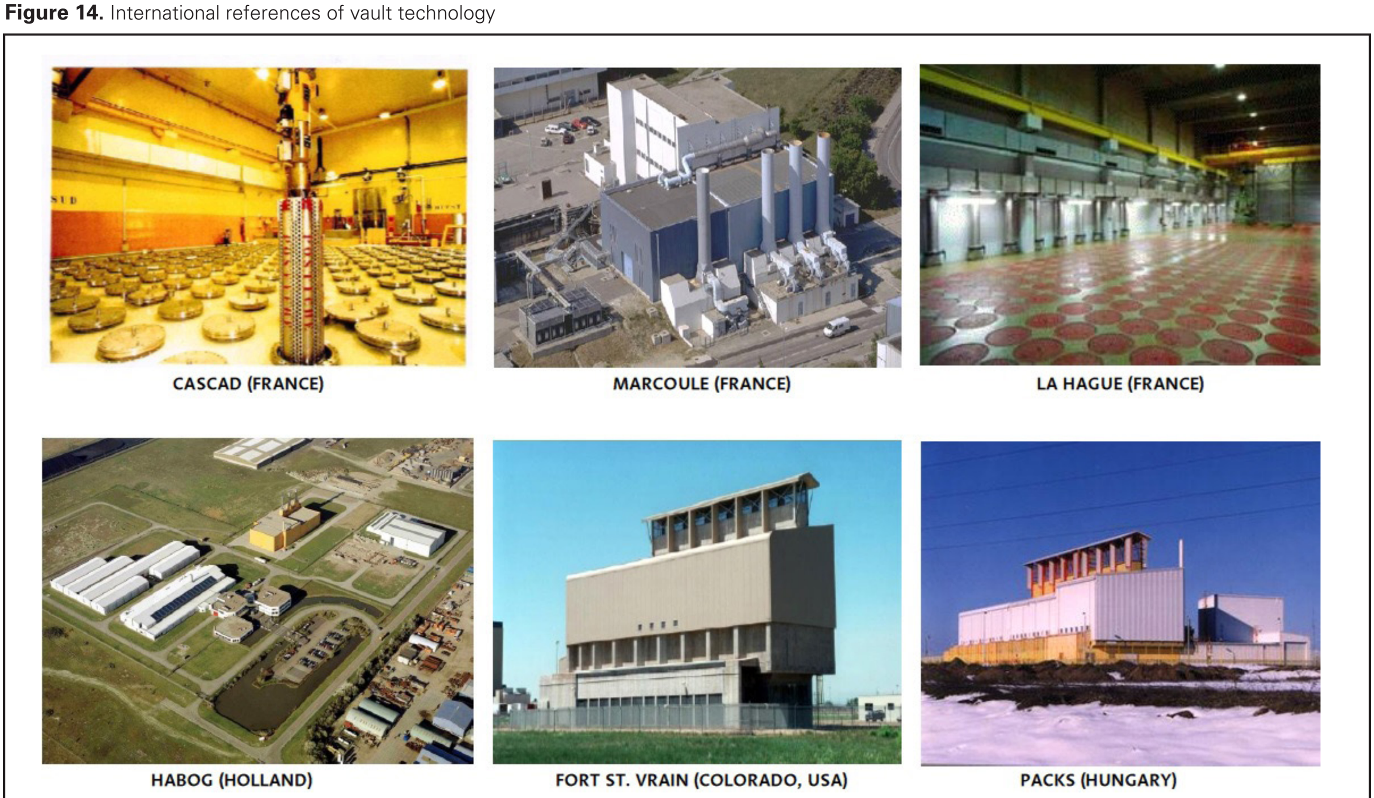


Figure 14. International references of vault technology



David Garrido obtained his mechanical engineering degree in 1997 and started his professional career in the nuclear industry in 1998 as structural and thermal analyst. A few years later, he became project manager of all the spent fuel cask fabrication at Ensa's facility. He has been leading the design and licensing team of the new ENSA's spent fuel cask design (ENUN) since 2008.

References

1. Source: REE (Red Eléctrica Española).
   Source: http://www.enresa.es.

Book Review

By Mark L. Maiello,
Book Review Editor

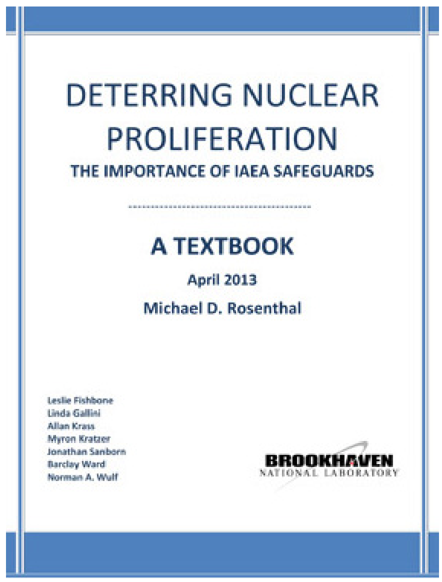
Deterring Nuclear Proliferation
The Importance of IAEA Safeguards
Michael D. Rosenthal, Leslie G. Fishbone, Linda Gallini, Allan Krass, Myron Kratzer, Jonathan Sanborn, Barclay Ward, and Norman A. Wulf

254 pages, available online at
www.bnl.gov/gars/NNS/IAEAtextbook.php

Brookhaven Science Associates, LLC, 2013

It took an ensemble of talented specialists to construct this textbook and the effort — which might have been botched unless properly orchestrated — resulted in a well-paced, evenhanded, and eminently comprehensible introduction to the mechanics of the International Atomic Energy Agency (IAEA) and the Nuclear Nonproliferation Treaty (NPT). This much needed introductory textbook complements the efforts of the Brookhaven National Laboratory Nonproliferation and National Security Department, which conducts an annual summer school for graduate students in the field of safeguards and security. The expertise harnessed for this effort appears to have been well matched to the task.

Students and other interested parties will find the text quite readable and, save for the unending acronyms that pervade the field, devoid of jargon. In fact, assuming a reader with interest in the subject, the book is relatively easy to digest. One need not be familiar with IAEA safeguards or the nuances of the NPT.



As a compliment to the aforementioned summer school, the book seems to have been written with the premise that young engineers, scientists, and those aspiring to policy-making or political science careers have little knowledge of nuclear weapons safeguards or the mechanics and legalities of their implementation. The authors triumph here, having produced a product that serves the novice as a foundation upon which future knowledge can find a firm footing. Further, precious little on just this subject matter is as accessible as this text.

The book is designed in a straightforward manner. Three large sections divide the material. Part I is a four chapter retrospective of the IAEA, its creation, nurturing, and organization. The NPT and the IAEA are a married pair, intimately bound. The courtship, wedding, honeymoon, and later phases of the relationship are aptly described here. Background chapters 1 and 2 review the status of nonproliferation and the mechanisms for maximizing its effectiveness. The culmination of Part I resides in the two chapters on statutes and mission of the IAEA and the negotiation and development of the NPT.

Part II explores NPT safeguards including the all important INFCIRC 153 that is the basis of all safeguards agreements. Two chapters on safeguards and their implementation lead the reader to Part III where it is explained that the original safeguards procedures have evolved into the current "model protocol." The final chapter looks at the future challenges of the IAEA, particularly its recent "state-level" approach to safeguards and the political hurdles it now faces. Five appendices follow. Technical information about the principles of nuclear arms, the creation of Euratom, the internal structure of the IAEA, safeguard agreements in nuclear-weapon states and the protocol agreement for those states at the opposite end of the spectrum, the so-called "small quantity protocol," are all covered.

One will find little, if any, subject matter on the technology of safeguards tools such as cameras, seals or satellite photography. By design, they are mentioned where an example is called for when discussing IAEA inspection strategies. The book steadfastly remains focused on the IAEA and NPT safeguards policy.

One of the book's strengths lies in its relatively fair assessment of the success of the IAEA and safeguards implementation. Neither too critical of the IAEA's failures nor enamored of its achievements, the authors have for the most part "said it like it is." True, the IAEA and the NPT have in fact been successful in mitigating the proliferation of nuclear weapons but the covert operation of weapons development in Iraq in the 1990s forced needed changes eventually resulting in the model protocol. As metaphorically explained by the authors, IAEA inspectors became detectives and moved away from being accountants. Such objectivity appears to have been successfully maintained throughout the text.

One cannot take the effort of constructing this text too lightly. A read-through will indicate that the authors had to synthesize their material from a plethora of sources to fully explain the issues they deemed important for an introduction to the subject. Immersion into a resource rich research effort requires care and attention to determine what students need to know as they enter the field. For example, the creation of the IAEA is discussed in detail in chapter 3. Following logically is a chapter on the development and implementation of the NPT. And, done in a rather understated way in Chapter 4, is a brief discussion of the coupling of the IAEA to the NPT (the IAEA administers the NPT safeguards) — a key point of learning, nicely handled so that even a novice can't miss it.

Throughout the text — but especially relevant to these chapters — the authors generously supply the surrounding historical and political context that allows the reader to grasp why these important agreements took the form they did.

This book was commissioned by the U.S. National Nuclear Security Administration and to an extent it resembles contracted work. The chapter-sections and subsections are numbered lending the feel of a report to what is billed as a textbook. A much needed index is missing — a shortcoming that might have been resolved with commercially available software. It is heavily footnoted, which by itself is not a problem and, in fact, is useful for the Internet links it provides. Since the book is an online production (see more remarks about this below), the practicality — if not the longevity — of the links are a plus to the student or researcher wishing to dive deeper into the subject. A glossary of terms and acronyms, so useful to students and the novice to the field, is also missing. Although there is a suggested reading list, neither a cumulative reference list nor chapter reference lists are provided. However, the many footnotes with links to references act to mitigate this limitation. A feature that brings the work back into the textbook arena is the provision of numerous, mostly helpful illustrations (consistent with policy, there is no list of figures).

Of note are more than a few printing errors of the typographical kind scattered throughout the text. These are not overly distracting but they are a reminder that the book was produced in-house and not at a professional publisher. This brings us paradoxically to another strength of the book. It is as mentioned above, freely available on the Internet.

College students and students of the graduate school variety are always at their maximum spending limits to the chagrin and shock of their parents and friends. Books in traditional hardcopy format and to an extent electronically (consider the cost of laptops, e-readers and other devices), remain a significant cost of education. Nonetheless, the zero cost of this book albeit ultimately funded from taxpayer money, is to be applauded. Anyone with a computer and the appropriate Internet connection can download it with just a minimum of effort. This is a celebration of free access to important learning and teaching information that should not go unnoticed.

The links to online resources so prevalent in the footnotes will, it is hoped, require periodic updating to keep this online resource current. It was noted disappointingly that links in this reviewer's downloaded version of the textbook were for whatever reason, not interactive. Perhaps this maintenance and the changes to the IAEA and other partner agencies and NPT signatories will provoke another edition. Recent examples of the dynamic nature of nonproliferation regime with potential impact on this text include the inauguration of a new IAEA Nuclear Material Laboratory in Austria that will support its role as detection agency, the November 2013 agreement curtailing Iran's nuclear program in exchange for the easing of sanctions, and what appears to be the impending admission of India into the Nuclear Suppliers Group. All can find eventual mention in a potential future edition of what already is a fine text book.

Professors, scholars, students, and interested laypeople should take note. This effort convincingly disproves the adage that "you get what you pay for."

Suggest a Book

Is there a book you would like to see reviewed in *JNMM*? Send the book title and author name to psullivan@inmm.org. Books must have been published no earlier than 2013 to be considered.

Taking the Long View in a Time of Great Uncertainty
Reflecting on the Health of the INMM

By Jack Jekowski
Taking the Long View Editor and Chair of the INMM Strategic Planning Committee

INMM unofficially became eligible this past year, by some definitions, to be called a "senior citizen," having achieved the age of fifty-five. For most people, and particularly for many "graying" Institute members, this is the age at which we begin to reflect upon the importance of maintaining our personnel health and how external factors and events can challenge our previous sense of invincibility.

When we step back and look at the Institute itself, we see a similar situation where a number of recent external factors have raised questions about the future health for the Institute, not the least of which are the economic issues facing all of our members; and other societal influences, including the restrictions placed on conferences in the United States due to some isolated inappropriate activities by some agencies. Despite these issues, the fundamental mission of the INMM remains sound, and the need for its contributions to the "nuclear world" is even more critical as we have entered the second decade of the 21st century, and increased our international presence.

How we effectively deal with these external influences from a strategic perspective will determine the future health and viability of the Institute, and should be a focus for all Institute members.

On-going Efforts to Adapt to Our New World

The INMM Executive Committee (EC) has put forth an enormous effort the past two years to mitigate the impact of these external influences, including the development of briefing materials, the engagement and partnering with other organizations with similar objectives, and the expansion of our communications strategies to promote the work of the Institute and the benefits offered to sponsors and supporters. Most recently, the Strategic Planning Committee (SPC) prepared a comparative analysis of the annual meetings of other key organizations, including the American Nuclear Society (ANS)[1] and the Health Physics Society (HPS),[2] as well as examining the importance of the timing and context of the IAEA International Conference on Nuclear Security,[3] held in 2013 within a month of the INMM Annual Meeting. Of note, these other organizations are also being impacted by external events. In the research done by the SPC, we found other organizations such as U.S. Women in Nuclear,[4] also have national meetings that could potentially conflict with INMM events. This analysis provides another important piece of information that can then be used by the EC to help develop long-range strategies (a "wellness program," if we stay with our health analogy) to continue to mitigate the impact of external events on the Institute.

The good news? We are responding to these situations with some success and continue to receive strong messages of encouragement, both verbally and in writing, from a wide range of supporters from within the United States as well as across the international community. Most importantly the mission and activities of the Institute have become more visible to a broader audience as fulfilling critical needs with respect to global nuclear safety and security needs.

All of this effort, of course, must also be within the context of an extraordinarily challenging time in the "nuclear community," with new geopolitical challenges seeming to rise up almost every day.

Aligning the Institute's Mission

Another tasking that the EC assigned to the SPC this spring was to examine the Institute's Mission in the context of this changing environment to ensure that our evolving strategies are properly focused.[5] This tasking grew from of a discussion while developing a "one-pager" information sheet on the Institute, as well as an effort by INMM Past President Steve Ortiz to review the Institute's bylaws to identify areas that need updating. It was noted that the Institute's mission statement has not been modified since the organizational realignment that occurred in 2010 and there was a desire to describe the Institute's mission in a single sentence for the one-pager. However, opinions for this single sentence differed, and as a result, the SPC, with assistance from the Fellows Committee and the Technical Divisions, is in the process of soliciting input on the Institute's mission statement and how we might describe the Institute in a shortened "elevator speech" statement.

As the World Turns

The mission of the Institute and the importance of the work conducted by its membership internationally remain even more important today. In past columns we have updated and discussed "Externalities" that influence the activities of the Institute.[6] This externalities assessment was one of the core activities performed by INMM President Ken Sorenson and the Organizational Strategic Planning Group in 2009 to examine the relevance of the Institute's organizational structure in the context of a dramatically different 21st Century, and has contributed to the development of a number of questions posed to the membership to stimulate strategic discussions on critical topics.[7] Since our look last year at this external environment we have seen a continuing, remarkable series of events, literally, "history in the making." These are but a few of those items of interest to the Institute in the context of our Mission:

- **Obama Brandenburg speech.** U.S. President Obama chose the historic location of the Brandenburg Gate in Berlin, Germany, on June 19, 2013, to reinforce his Prague 2009 vision of a world without nuclear weapons. Of note, he suggested that a strong and credible strategic deterrent could be maintained by the United States while reducing deployed nuclear weapons by up to one third (down to a level of approximately 1,000):

  "Peace and justice means pursuing the security of a world without nuclear weapons — no matter how distant that dream may be…and we can forge a new international framework for peaceful nuclear power, and reject the nuclear weaponization that North Korea and Iran may be seeking."[8]

  Regime change once again in Egypt. The continuation of the "Arab Spring" disruptions in the Middle East brought about yet another regime change in Egypt last year. The complex environment in the Middle East continues to challenge the diplomatic approach that is emblematic of the U.S. National Security Strategy.[9]
- **Diplomatic resolution to Syrian chemical weapons.** The challenge presented to the world with the use of chemical weapons in the Syrian War was resolved diplomatically on the eve of threatened military action. Challenges still exist to implement the agreed-upon actions to eliminate the stockpile in the midst of a continuing conflict.
- **U.S. Government Shutdown.** The shutdown of the U.S. government in October 2013 impacted many of our members and their organizations, including an INMM-sponsored Risk Reduction workshop planned for Stone Mountain, Georgia, USA, during that time, requiring it to be moved to February of this year.[10] The possibility of similar disruptions in the future creates critical uncertainties for not only our membership, but the Institute itself.
- **Diplomatic resolution to the Iranian nuclear situation.** In a remarkable sequence of diplomatic maneuvers following the Iranian election in June of moderate Hassan Rouhani, a "Joint Plan of Action" was negotiated between Iran and the "P5+1" (China, France, Germany, Russia, United Kingdom, and the United States), who agreed on a six-month "first step" of limitations on the Iranian nuclear program and reductions in some sanctions, leading within a year to a "comprehensive solution." This would deescalate the tensions between Iran and the world over their nuclear program. Although there are still dissenting voices over the negotiated agreement in the United States, in Iran, and internationally, this challenge represents the ultimate test of the Obama administration's national security position, "*Diplomacy is as fundamental to our national security as our defense capability. Our diplomats are the first line of engagement, listening to our partners, learning from them, building respect for one another, and seeking common ground.*"[11]
- **Escalation of tensions over Senkaku/Diaoyu Islands in the East China Sea, and territorial claims in the South China Sea.** The longstanding territorial conflict over islands in the East China Sea (Senkaku/Diaoyu) took on a new dimension recently as China established an "air defense identification zone" (ADIZ) requiring all foreign aircraft to identify themselves and the reason for being in the zone. This was challenged almost immediately by two U.S. B-52 bombers that flew through the zone without annunciation. More recently, tensions increased over territorial claims in the South China Sea over territorial waters and shoals claimed by the Philippines and other countries. U.S. Vice President Joe Biden opened dialog with Chinese leaders in a Far East visit recently to attempt to resolve these issues. Unfortunately, this escalation of tensions in the Far

East only further complicates the international environment that challenges the world today.

- **Theft of Cobalt-60 source in Mexico.** A container of medical Cobalt-60 radioactive material was stolen in Mexico, and found two days later. It appears the container was not the target for theft, but rather the transport vehicle. When found two days later, the source had been opened and the individuals who stole it unknowingly exposed themselves to significant radiation. Early reaction was worldwide — asking the IAEA to strengthen international standards for waste shipments.[12]
- **Annexation of Crimea by Russia.** The events that have unfolded in the Crimea have impacted the continuity of scientific and other collaborations that have been building between the international community and many INMM member organizations, including the open exchange of information at the Institute's annual meeting and technical workshops. Additionally, these events have opened discussions in the media and elsewhere on some of the more important nonproliferation issues associated with national security and nuclear weapons in other states. Although the Institute does not inject itself at these levels, it behooves the membership to understand and discuss the complex interactions events such as this might have on the ability to accomplish its mission of enhancing global safety and security.
- **Third Nuclear Security Summit held in The Hague.** The third Nuclear Security Summit was hosted by the Netherlands at The Hague in late March. Initiated by President Obama in 2010, this international gathering has been held every two years, with the fourth, and possibly final, summit now scheduled to be held in Washington, D.C., in 2016. One document that came out of this year's Summit, "Strengthening Nuclear Security Implementation," was a declaration, signed by thirty-five of the fifty-three states attending, intended to bring the international community closer in their efforts to strengthen the security of their nuclear materials. This agreement and a final Summit Communiqué are available at the Summit's website.[13] Understanding and discussing consensus documents such as these is an important part of a continuous "environmental scan" that we must all to ensure that the focus of the Institute's mission is proper, and that our priorities are appropriately placed.

While we work these issues that directly affect the health of the Institute and the safety and security of nuclear materials worldwide, we can expect more history-making events in 2014, as the geopolitical world of the 21st Century has evolved into a complex and ever-changing landscape. The mission of the INMM and the efforts of its international membership continue to fulfill a critical global need, but now must be accomplished in a very different external environment. It is important that our membership promote the accomplishments and capabilities of the Institute within their spheres of influence, and join in strategic discussions to ensure the future health and viability of the organization.

This column is intended to serve as a forum to present and discuss current strategic issues impacting the Institute of Nuclear Materials Management in the furtherance of its mission. The views expressed by the author are not necessarily endorsed by the Institute, but are intended to stimulate and encourage JNMM *readers to actively participate in strategic discussions. Please provide your thoughts and ideas to the Institute's leadership on these and other issues of importance. With your feedback we hope to create an environment of open dialogue, addressing the critical uncertainties that lie ahead for the world, and identify the possible paths to the future based on those uncertainties that can be influenced by the Institute. Jack Jekowski can be contacted at jpjekowski@aol.com.*

Endnotes

1. See http://www.ans.org
2. See http://www.hps.org
3. See http://www-pub.iaea.org/iaeameetings/43046/International-Conference-on-Nuclear-Security-Enhancing-Global-Efforts
4. See www.winus.org
5. See Jekowski, J. Looking Back at a Decade of Tumult — and Looking Forward to an Uncertain Future. *Journal of Nuclear Materials Management*, Volume 40, No. 3, pp. 99-101 for a discussion of the Institute's mission in the context of historical events and the uncertainties of the future.
6. Jekowski, J. Readjusting Priorities. *Journal of Nuclear Materials Management*, Volume 41, No. 3, pp. 20-22.

7. Jekowski, J. Looking Back at a Decade of Tumult — and Looking Forward to an Uncertain Future. *Journal of Nuclear Materials Management*, Volume 40, No. 3, pp. 99-101
8. http://www.whitehouse.gov/the-press-office/2013/06/19/remarks-president-obama-brandenburg-gate-berlin-germany
9. Jekowski, J. As the World Turns… Toward a More Dangerous Place. *Journal of Nuclear Materials Management,* Volume 41, No. 4, pp. 111-113.
10. See http://www.inmm.org/Past_Events.htm
11. See U.S. National Security Strategy, May 2010, p. 14 http://www.whitehouse.gov/sites/default/files/rss_viewer/national_security_strategy.pdf
12. See http://iaea.org/newscenter/news/2013/mexicoradsource2.html and http://www.nti.org/gsn/article/after-mexican-theft-critics-question-if-iaea-radiological-security-rules-are-enough/ for more information on this event.
13. https://www.nss2014.com/en

Author Submission Guidelines

The *Journal of Nuclear Materials Management* is the official journal of the Institute of Nuclear Materials Management. It is a peer-reviewed, multidisciplinary journal that publishes articles on new developments, innovations, and trends in safeguards and management of nuclear materials. Specific areas of interest include facility operations, international safeguards, materials control and accountability, nonproliferation and arms control, packaging, transportation and disposition, and physical protection. *JNMM* also publishes book reviews, letters to the editor, and editorials.

Submission of Manuscripts: *JNMM* reviews papers for publication with the understanding that the work was not previously published and is not being reviewed for publication elsewhere. This restriction includes papers presented at the INMM Annual Meeting. Papers may be of any length. All papers must include an abstract.

The *Journal of Nuclear Materials* Management is an English-language publication. We encourage all authors to have their papers reviewed by editors or professional translators for proper English usage prior to submission.

Papers should be submitted as Word or ASCII text files only. Graphic elements must be sent in TIFF, JPEG or GIF formats as separate electronic files.

Submissions may be made via e-mail to Managing Editor Patricia Sullivan at psullivan@inmm.org. Submissions may also be made via by regular mail. Include one hardcopy and a CD with all files. These submissions should be directed to:

Patricia Sullivan
Managing Editor
Journal of Nuclear Materials Management
111 Deer Lake Road, Suite 100
Deerfield, IL 60015 USA

Papers are acknowledged upon receipt and are submitted promptly for review and evaluation. Generally, the corresponding author is notified within ninety days of submission of the original paper whether the paper is accepted, rejected, or subject to revision.

Format: All papers must include:
- Corresponding author's complete name, telephone number and e-mail address
- Name and address of the organization where the work was performed
- Abstract
- Tables, figures, and photographs in TIFF, JPEG, or GIF formats. Color is encouraged.
- Numbered references in the following format:
  1. Jones, F.T., and L. K. Chang. 1980. Article Title. *Journal* 47(No. 2): 112–118. 2. Jones, F.T. 1976. *Title of Book*, New York: McMillan Publishing.
- Author(s) biography

JNMM is published digitally in full color. Color graphics and images are encouraged.

Peer Review: Each paper is reviewed by at least one associate editor and by two or more reviewers. Papers are evaluated according to their relevance and significance to nuclear materials safeguards, degree to which they advance knowledge, quality of presentation, soundness of methodology, and appropriateness of conclusions.

Author Review: Accepted manuscripts become the permanent property of INMM and may not be published elsewhere without permission from the managing editor. Authors are responsible for all statements made in their work.

Reprints: Reprints may be ordered at the request and expense of the author. Contact Patricia Sullivan at psullivan@inmm.org or +1-847-480-9573 to request a reprint.

June 10–12, 2014
WINS Security of Dry Storage of Spent Nuclear Fuel International Best Practice Workshop
Novotel Vilnius Centre
Vilnius, Lithuania

July 20–24, 2014
INMM 55th Annual Meeting
Atlanta Marriott Marquis
Atlanta, Georgia USA
Website:
www.inmm.org/AM55

August 24–28, 2014
8th International Conference on Isotopes and Expo
Hyatt Regency Hotel
Chicago, Illinois USA
Website:
www.8ici.org

October 20–24, 2014
Symposium on International Safeguards: Linking Strategy, Implementation and People
Vienna, Austria
Organized by the International Atomic Energy Agency (IAEA) in cooperation with the European Safeguards Research and Development Association (ESARDA) and the Institute of Nuclear Materials Management

January 12–14, 2015
INMM 29th Spent Fuel Seminar
Crystal Gateway Marriott Hotel
Arlington, Virginia USA
Website:
www.inmm.org

September 11–16, 2016
PATRAM 2016
Kobe Portopia Hotel
Kobe, Japan