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Guideline for the Implementation of Safeguards into the Design Process for Nuclear Reactors

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Technical Basis Document

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REPORT SUMMARY

This report provides the technical basis for a process to implement Safeguards-by-Design (SBD) into the design process for nuclear facilities.

Background
The designs of all nuclear facilities are subject to many economic, technical, legal, security, safety, environmental and other constraints, and it is the function of the design team to find solutions which are optimal within these constraints. Implementation of international safeguards by the International Atomic Energy Agency (IAEA) is an additional factor which should be taken into account, preferably during the design stage [1]. This report has been prepared with the aim of contributing to the incorporation of international safeguards relevant features in the design of future plants in order to:

- Minimize the burden of international safeguards implementation on plant operations
- Promote better understanding of safeguards operations and needs by reactor designers
- Minimize the cost of safeguards, including the burden on IAEA inspection resources
- Improve, for both operators and inspectors, the conditions under which IAEA safeguards inspections are conducted
- Take advantage of advances in safeguards technologies
- Ensure the effectiveness of the international safeguards regime and promote advances in the quality, methods of acquisition and integrity of safeguards data

Objective
To develop a pragmatic process that addresses implementing Safeguards-by-Design into the design process for nuclear reactors that is satisfactory to all stakeholders (designer/vendor, owner/operator, regulatory authority, and the International Atomic Energy Agency)

Approach
Safeguards of the International Atomic Energy Agency (IAEA) are a central part of international efforts to stem the spread of nuclear weapons. In implementing safeguards, the IAEA plays an independent verification role, ensuring that States' safeguards commitments are met. All nuclear facilities and nuclear materials in Non-Nuclear Weapons States (NNWS) that are Parties to the Nuclear Nonproliferation Treaty (NPT) must be under IAEA safeguards. In addition, the five nuclear weapon states recognized under the NPT (the United States, China, the United Kingdom, Russia, and France) have undertaken voluntarily to make some or all of their civil nuclear facilities eligible for selection by the IAEA for international safeguards. India has agreed to segregate its purely civil nuclear facilities, including some existing and future power reactors, from the rest of its nuclear program and accept IAEA safeguards at these civil nuclear facilities. As a result, regardless of whether the IAEA might, or might not, select a U.S. domestic power reactor for safeguards, U.S. designers of nuclear reactors can anticipate that their prospective

customers in NNWS NPT States will be subject to IAEA safeguards, and correspondingly might find value in reactor designs considered are readily "safeguardable" by the IAEA. The IAEA presently is developing and publishing a series of Safeguards-By-Design (SBD) Guides to help designers and operators of specific types of nuclear facilities better understand how the design of such nuclear facilities can facilitate the implementation of international safeguards. In parallel, the U.S. National Nuclear Security Administration's (NNSA) Office of Nonproliferation and International Security, through its Next Generation Safeguards Initiative (NGSI), has published a series of facility-specific SBD guides and related lessons-learned analyses that were developed by several Department of Energy national laboratories. This report draws heavily upon these studies to create a coherent compendium of lessons learned, IAEA safeguards authorities and needs, and best practices for Safeguards-by-Design. As such, no new studies have been conducted as part of the development of this report, but rather the salient points and sections from various cited results have been collected and expanded upon herein.

EPRI Perspective

[EPRI insert their preferred text here]

Results
This report presents general and some specific guidelines for implementing Safeguards-by-Design that is consistent with IAEA safeguards needs while at the same time minimizing the burden on other stakeholders. Results from multiple other studies have demonstrated that early implementation of Safeguards-by-Design not only assists the IAEA with their safeguards needs, but also ultimately reduces stakeholder costs.

Keywords
Safeguards
Proliferation
Design

FOREWORD

It is recognized that nuclear power plant designers, as part of the vendor organization, as well as the intended owner/operator all desire to minimize total costs and risks associated with the design, construction and operation of such plants. All nuclear facilities in Non-Nuclear Weapons States that are Party to the Nuclear Nonproliferation Treaty (NPT) are subject to IAEA safeguards, as are facilities in the United States that are selected by the IAEA for implementation of its safeguards. Although the chances of IAEA selection of a U.S. domestic power reactor for safeguards are remote, U.S. reactor designers should anticipate that their prospective NNWS customers will have to meet IAEA safeguards requirements. It has been found through multiple case studies that implementing safeguards late in the process can often result in significantly increased costs associated with re-designing and retrofitting plants which have not adequately taken IAEA safeguards needs into account earlier in the design process. This report is intended to present guidelines to the designers of future nuclear power plants which, if taken into account in the design of these plants, could help to minimize the impact of IAEA safeguards on plant operations and ensure efficient and effective safeguards implementation to the mutual benefit of the Member State, the plant operator and the IAEA.

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INTRODUCTION

1.1 Purpose

The purpose of this report is to create the technical basis for a structured approach to implementing Safeguards-by-Design (SBD) guidance into the design process for nuclear power plants (NPPs). This effort can provide the following benefits to the nuclear industry:

- Design guidance that will better facilitate implementation of nuclear safeguards required by the International Atomic Energy Agency (IAEA)
- Background information on efficiently maintaining nuclear material accountability, as specified by the IAEA
- Lessons learned from previous safeguards implementation issues which have fostered development of a Safeguards-by-Design approach that will minimize costs associated with retrofitting late-stage designs to accommodate required safeguards
- Background on IAEA statutory authorities

The intent is to provide a pragmatic approach for SBD that satisfies the needs of the IAEA while at the same time minimizing the impact to vendors and operators. It is important to note that SBD for international safeguards is voluntary and is not a legal requirement under IAEA safeguards, though an individual Safeguards Regulatory Authority (the national agency responsible for the State's implementation of its IAEA safeguards requirements) might strongly encourage it. SBD is supposed to provide flexibility for designers to meet overall IAEA safeguards needs [2]. Recent experience in Finland [3] has highlighted that implementation of safeguards late in the design process, often after most construction is complete, can require costly re-design and retrofitting of the facility and unwelcome delays. Safeguards implementation at the Rokkasho reprocessing plant in Japan showed that SBD initiation and dialogue with the IAEA early in the design process is critical [4]. Additionally, with trends towards standardized, and in some cases regulator-certified, NPP designs, rather than individual designs for specific locations, a safeguards-by-design approach would be of further value, particularly for Small Modular Reactors (SMRs) [5] [6], to ensure that the design can readily accommodates the safeguards measures the IAEA might apply

1.1.1 Problem Statement

The Non-Proliferation Treaty (NPT) obligates all non-nuclear weapon states (NNWS) parties to allow the IAEA to implement safeguards on all nuclear materials and activities within their countries. The five Nuclear Weapon States recognized by the NPT (USA, UK, France, Russia, China) have voluntarily made some or all of their civil nuclear facilities eligible for selection by the IAEA for international safeguards. Much of the planned and projected growth in nuclear power generation is in NNWS countries, so vendors designing NPPs for these regions, as well as the operator and regulator, must be prepared for full implementation of IAEA safeguards at such facilities.

While the IAEA does not in general implement full safeguards into U.S.-based nuclear power plants (NPPs), U.S. civilian NPPs are on the "eligible facilities" list for safeguards. Historically some U.S. nuclear reactor facilities were under safeguards, but none have been selected by the IAEA for safeguards since the 1980s. At present (2013), only portions of a plutonium storage facility at the Department of Energy's Savannah River Site is under IAEA safeguards, and several U.S. low-enriched uranium fuel fabrication facilities are required to submit nuclear material accounting reports to the IAEA. In addition, with the entry into force of the Additional Protocol (AP) to the United States-IAEA Safeguards Agreement in 2009, a wide range of U.S. nuclear fuel cycle-related activities that do not involve nuclear material, including research and development on reactors and fabrication of certain critical components for such, must be declared annually to the IAEA, and the locations of these activities are subject to IAEA Complementary Access. U.S. reactor designers should consult the Nuclear Regulatory Commission or the Department of Commerce to determine what they must do to meet reporting obligations under the U.S. AP. [7]

Multiple studies [1] [2] [8] [9] [10] [11] have demonstrated that SBD early in the design process facilitates more efficient implementation of safeguards, minimizes costs inevitably involved in late-stage retrofitting of NPPs for safeguards (which may be borne by the vendor and/or operator), and provides confidence to designers and other stakeholders that safeguards design considerations will be adequate and acceptable to the IAEA and its safeguards mission at safeguarded nuclear facilities.

The nuclear industry is still in need of a central compendium of SBD guidelines and SBD best practices to encourage the actual implementation of SBD. Publication of this Technical Basis Document by EPRI based on the results of multiple SBD studies will help satisfy this need.

1.2 Scope

The scope of SBD guidelines applies primarily to designers of nuclear facilities, especially those facilities destined for non-U.S. markets. However, since SBD is an overall project management undertaking [2], other stakeholders such as the owner/operator and regulator should be involved in the process. Safeguards-by-Design guidelines encompass design considerations that will minimize potential diversion routes of nuclear material, facilitate implementation of IAEA safeguards measures, and improve access by IAEA inspectors to nuclear material balance areas needed to verify that no diversion of material has occurred. A description of IAEA statutory authorities for implementing safeguards is also be provided.

1.3 Project Objective

The objective of this project is to provide technical guidance and basis for use by the industry as to SBD processes which will better facilitate implementation of required IAEA safeguards in a cost-effective manner by: 1) providing a background on IAEA safeguards and international obligations thereto, and 2) providing specific IAEA needs and design solutions for reactors that have been identified in multiple studies on SBD implementation.

1.4 Background

It should be pointed out first that SBD is a voluntary process; the IAEA has no direct authority to insist on the incorporation of specific design features in any facility [1]. Countries are not obligated to utilize SBD prescriptions as part of any treaties. [12] However, it is envisioned that stakeholders (vendors, operators, regulators, the IAEA) will all benefit if SBD is utilized. Also, the responsibility for SBD does not rest solely with the designer; rather, SBD is an ongoing dialogue among the designer/vendor, the owner/operator, the regulatory body, and the IAEA.

It must also be stressed that SBD is *not* equivalent to proliferation resistance. It is crucially important to consider separately the risks of diversion of nuclear material from an IAEA-safeguarded nuclear facility by the host State or misuse of such a facility by the State to produce undeclared nuclear material in support of developing nuclear weapons, and the very different risks posed by a non-State actor (e.g., an "insider", a sub-national terrorist group) to steal nuclear materials for use in a nuclear device or commit an act of radiological sabotage. [13] The term "proliferation" should be reserved to the State proliferation risk, to be consistent with how the term is used in the nonproliferation community. Effective IAEA safeguards are of fundamental performance to addressing State risks, and as a recent Department of Energy report observes, while there is no technological "solution" to this risk, different technologies and facility designs can differ in how readily safeguardable they are. Hence, safeguards-by-design might involve not only efforts in the design process that make implementing safeguards at the facility easier for the IAEA, such as space for equipment, minimal entry points, unmanned monitoring systems, etc., it might also involve steps to eliminate a particular diversion path from the design, where consistent with other considerations such as safety and economics. Nonetheless, having said this, the reader should understand that the protection of nuclear materials and facilities against forcible seizure, theft, terrorism and other criminal activities is the responsibility of the State, not of the IAEA [1], and is not addressed by IAEA safeguards. (To keep nomenclature clear, these non-state risks should be referred to in terms of security or physical protection risks, and not in terms of "proliferation resistance.")

Unlike safety, international safeguards may be a little-known area for many designers. Historically, international safeguards have had to be retrofitted into facilities at very advanced stages of construction after the design process had been completed, and facilities had not been designed to accommodate IAEA safeguards. In the United States, domestic nuclear facilities were selected historically for IAEA safeguards after they had entered into operation. This led to a perception that international safeguards are beyond the scope of the facility design team and not suitable for their consideration. However, when international safeguards considerations are addressed early in a project, experience has shown that the implementation cost is less than 0.1 % of the capital cost of a nuclear power plant. Incorporating SBD into the design/build/operational process has the potential benefits of:

- Minimizing project risk against cost and schedule
- Improving international safeguards implementation
- Reducing operator burden
- Minimizing IAEA inspector time in a facility
- Increasing flexibility for future IAEA safeguards equipment installation
- Facilitating considerations of joint use (operator-inspectorate) equipment
- Reducing the need to retrofit for installation of IAEA safeguards equipment

In recent years, both the IAEA and the National Nuclear Security Administration's Next Generation Safeguards Initiative have developed a number of reports and guides on SBD. These results have shown that enhanced efficiency and safeguards effectiveness can be gained by: 1) relying on proven safeguards design concepts based on lessons learned, and 2) optimizing nuclear facility features not typically affected by safeguards requirements, such as the plant's layout [8].

The IAEA Department of Safeguards understands that through careful planning safeguards systems and processes could be implemented that could increase the capability of safeguards organizations to detect the diversion of nuclear material and the misuse of a facility more effectively and efficiently, could be less intrusive to facility operators, and potentially could result in a lower total cost to the stakeholders. With this goal in mind, the Department of Safeguards is working with experts from Member States to develop the concept of 'safeguardability' and to develop documentation that can serve as guidance for the inclusion of safeguards considerations at an early stage of future nuclear technology designs [9].

The IAEA SBD documents are accessible at http://www.iaea.org/safeguards/Resources_for_States/additional-documents.html. A number of facility-specific SBD Guides will be published by the IAEA over the coming two years (2013-2014). The NNSA SBD Guides can be accessed at www.nnsa.energy.gov/safeguardsbydesign. This document draws very heavily on the IAEA SBD Guide for Reactors. [13]

The discussion of SBD for international safeguards at reactors that follows in this report focuses primarily on particular IAEA safeguards measures that are implemented at reactors, and certain safeguards issues that different kinds of reactors might pose. Although presentation of a methodology to assess the safeguardability of a nuclear facility is beyond the scope of this report, NNSA NGSI has developed a Facility Safeguardability Assessment tool to help a facility designer, working with one or more international safeguards subject matter experts as part of its design team, anticipate whether there are elements of its proposed facility design, and in particular innovative design features, that might pose a new or unforeseen safeguards issue that can be addressed through SBD. Use of this tool can help orient the design team to address these issues, and to help facilitate discussions with a State's Safeguards Regulatory Authority and the IAEA on international safeguards for the facility. [6], [14] The questionnaire used in this Facility Safeguardability Assessment approach is to be found at Appendix B to this report.

The designer should understand that in the final analysis, the IAEA will determine what safeguards approach it will apply to a particular facility, and the specific safeguards measures it will require. Early discussions of potential safeguards issues and challenges with the IAEA Department of Safeguards, working through the Safeguards Regulatory Authority, can facilitate early resolution of these issues.

2
IAEA SAFEGUARDS

The purpose of the safeguards system of the IAEA is to provide credible assurance to the international community that nuclear material remains in peaceful nuclear activities. [15] Towards this end, the safeguards system consists of several interrelated elements:

- the Agency's statutory authority to establish and administer safeguards
- the rights and obligations assumed in safeguards agreements and additional protocols
- the verification measures implemented pursuant to those agreements

Taken together, these elements enable the IAEA to independently verify the declarations made by States about their nuclear material and activities.

The IAEA safeguards system has three State level objectives:

- To detect undeclared nuclear material and activities in the State as a whole.
- To detect undeclared production or processing of nuclear material in declared facilities and locations outside facilities[a] (LOFs).
- To detect the diversion of declared nuclear material in declared facilities and LOFs.

The IAEA has established detection/inspection goals for each type of nuclear material with both a quantity component and a timeliness component. The quantity component relates to the quantity of nuclear material necessary for use in a weapon; the timeliness component to the complexity of activities necessary for the processing of nuclear material for weapons use. Two of the three State-level objectives involve safeguards implemented at nuclear facilities.

2.1 Safeguards Statutory Authorities

States enter into safeguards agreements with the IAEA in order to fulfill their non-proliferation commitments [11]. Each non-nuclear-weapon state (NNWS) party to the *Treaty on the Non-Proliferation of Nuclear Weapons* (NPT) [12] is required to conclude a Comprehensive Safeguards Agreement (CSA) with the IAEA. A listing of countries and their respective safeguards agreements can be found at http://www.iaea.org/safeguards/documents/sir_table.pdf. The basis for CSAs in connection with the NPT is provided in *The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons* (hereafter referred to as INFCIRC/153) [13]. Under a CSA, the State undertakes to accept IAEA safeguards on all source or special fissionable material in all peaceful nuclear activities within the territory of the State, under its jurisdiction or carried out under its control anywhere. For its part, the IAEA has the corresponding right and obligation to

[a] LOF is defined in Annex II: Terminology

ensure that safeguards are applied on all source or special fissionable material for the exclusive purpose of verifying that such material is not diverted to nuclear weapons or other nuclear explosive devices, or for purposes unknown.

"Voluntary offer" agreements have been concluded between the IAEA and the five nuclear weapon States (NWS) that are party to the NPT (USA, UK, France, Russia, and China). Those States are not required by the NPT to accept safeguards, but have voluntarily offered to do so. In addition, the IAEA applies safeguards under facility-specific safeguards agreements, based on the provisions in document INFCIRC/66/Rev 2, *The Agency Safeguards System* [14], in a few States that are not NPT Parties. Under such agreements, the IAEA is required to ensure that the nuclear material and other specified items (which may include, for example, nuclear material and nuclear facilities) are used only for peaceful purposes and are not used to manufacture nuclear weapons or other nuclear explosive devices, or to further any military purpose.

A State may also conclude a protocol additional to its safeguards agreement. IAEA document INFCIRC/540 (Corrected), *Model Protocol Additional to the Agreement(s) between States and the IAEA for the Application of Safeguards* [15] provides the basis for States' Additional Protocols (AP). Under an AP, a State is required to provide to the IAEA broader access to information and locations related to the State's nuclear fuel cycle than is provided under a CSA. While the U.S. as a NWS was not obligated to enter into an AP with the IAEA, the U.S. voluntarily did so as a confidence-building gesture, which went into effect in 2009. As noted earlier, research and development activities not involving nuclear material, such as development design of nuclear reactors, and manufacture of reactor control rods, are declarable annually to the IAEA as part of the national AP declaration.

The basic undertaking of the IAEA under a CSA as stated in INFCIRC/153 (paragraphs 2 & 7) requires the IAEA to independently reach its safeguards conclusions. IAEA verification activities may include, among other things, inspections, use of IAEA-approved equipment for measurements and monitoring, assuring authenticity of safeguards data, installation of IAEA equipment at facilities, application of seals to IAEA equipment used and stored at facilities, analysis of environmental and nuclear material samples at IAEA laboratories, and verification of the functioning and calibration of equipment using certified reference materials (such as weight standards or enrichment standards). In addition, IAEA design examination and verification, which are discussed further below, are important elements in the IAEA's development of a safeguards approach to a specific nuclear facility.

INFCIRC/153 Paragraph 2 The Agreement should provide for the Agency's right and obligation to ensure that safeguards will be applied in accordance with the terms of the Agreement on all source or special fissionable material in all peaceful nuclear activities within the territory of the State, under its jurisdiction or carried out under its control anywhere, for the exclusive purpose of verifying that such material is not diverted to nuclear weapons or other nuclear explosive devices.
INFCIRC/153 Paragraph 7 The Agreement should provide that the State shall establish and maintain a system of accounting for and

control of all *nuclear material* subject to safeguards under the Agreement, and that such safeguards shall be applied in such a manner as to enable the Agency to verify, in ascertaining that there has been no diversion of *nuclear material* from peaceful uses to nuclear weapons or other nuclear explosive devices, findings of the State's system. The Agency's verification shall include, inter alia, independent measurements and observations conducted by the Agency in accordance with the procedures specified in Part II below. The Agency, in its verification, shall take due account of the technical effectiveness of the State’s system.

The IAEA is obligated to achieve certain objectives relevant to each type of safeguards agreement. The safeguards objective of a CSA is defined in paragraph 28 of INFCIRC/153.

INFCIRC/153 Paragraph 28

The Agreement should provide that the objective of safeguards is the timely detection of diversion of significant quantities of *nuclear material* from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection

The ‘timely detection’ of the diversion of ‘significant quantities’ is based on the premise that, if a certain quantity of fissile nuclear material cannot be accounted for, the possibility of the State manufacturing a nuclear explosive device cannot be excluded. Also, a certain length of time is required for the State to convert nuclear material into a weapon-usable form. Goal quantities and timeliness requirements are established for detecting diversion of different categories and forms of nuclear material (e.g. low-enriched uranium and highly-enriched uranium; bulk form or fresh reactor fuel assemblies). The IAEA definitions of significant quantities of nuclear material are shown below in **Error! Reference source not found.**Table 2-1. Also, timely detection depends upon the type and state of the nuclear material.

Table 2-1
Significant quantities of nuclear materials and their misuse/diversion detection goals

Material Category	Material Type	Significant Quantity (SQ)	Timeliness Detection Goal
Indirect Use	LEU*	75 kg	1 year
	Natural U, Th	10 tons	1 year
	Irradiated Pu	8 kg	3 months
Direct Use	Pu	8 kg	1 month
	HEU*, U-233	25 kg	1 month

*LEU and HEU significant quantity limits apply to U-235 mass

Familiarity with the processes, layout, equipment and other characteristics of a given nuclear facility is essential for developing a facility specific safeguards approach, for carrying out verification activities and for understanding how that approach and the facility relate to an overall safeguards approach for the State. Facility design information is examined and verified by the IAEA for the purposes of evaluating material flows and inventories, determining the structure of Material Balance Areas (MBAs) and designing the safeguards approach. Design information is periodically re-verified to ascertain its continued accuracy, determine whether the current safeguards approach needs to be modified, assess whether new methods for accountancy verification or for containment and surveillance are needed, and confirm that the Facility Attachment remains valid.

For planned facilities, the early provision of design information provides adequate lead time for the IAEA and the SRA to cooperate in preparing for safeguards implementation. All States subject to safeguards must notify the IAEA as early as possible regarding plans for a new facility. When a State anticipates building a facility, the preliminary information about the planned facility may be provided to the IAEA in a Design Information Questionnaire (DIQ) or as free text in a letter. The early notification may include only very basic information, such as "two light water reactors, approximately 700 MW each." As decisions are made about the specific design, additional information should be provided to the IAEA, including the physical location, preliminary design drawings, plant process layouts, etc. The dialog between the IAEA and the State should begin very early in the process of planning to build a nuclear facility. This cooperation allows for features to be incorporated into the facility design which support safeguards implementation, which may save money over the lifetime of the facility operation.

The early provision of preliminary design information is required of all States with CSAs, as described in GOV/2554/Attachment 2/Rev.2 of 1992, entitled *Strengthening of Agency Safeguards – the Provision and Use of Design Information* and noted by the Board in the Chairman's summary published in GOV/OR.777 in February of 1992. Code 3.1 of the model Subsidiary Arrangements (General Part) was subsequently modified to incorporate the Board's decision, requiring the early provision of design information for new facilities beginning in the project definition stage, with additional information provided on an iterative basis as the project progresses. States must notify the IAEA as soon as the decision to construct or to authorize construction, whichever is earlier, has been taken.

The IAEA's right to examine and verify design information extends throughout the lifecycle of the facility - from before construction through to final decommissioning. In the early stages of the project, the IAEA works with the SRA to identify and schedule actions that need to be taken jointly by the State, the facility operator and the IAEA, such as discussing the IAEA's safeguards approach, installing safeguards equipment and conducting design information examination and verification visits during construction. Collaborative planning among the IAEA, the SRA and the operator can lead to significant improvement of the effectiveness and efficiency of safeguards, as well as reductions in the impact on facility operations, especially when new nuclear technologies and new facility types are involved.

When the IAEA has determined for safeguards purposes that a facility has been decommissioned, it may confirm the continued decommissioned status of the facility in States with an AP, using complementary access to verify that all nuclear material has been removed and the facility in fact has been decommissioned.

The IAEA is obligated to adhere to requirements specified in CSAs in designing and implementing its safeguards approaches and activities. The IAEA must implement safeguards in a manner designed to avoid undue interference in facility operations and hampering of States' economic and technological development. The IAEA must also protect State information, make full use of the State's system for accounting and control of nuclear material, and take advantage of technological advancements in safeguards to achieve cost efficiencies.

INFCIRC/153 Paragraph 4 The Agreement should provide that safeguards shall be implemented in a manner designed: (a) to avoid hampering the economic and technological development of the State or international co-operation in the field of peaceful nuclear activities, including international exchange of nuclear material; (b) to avoid undue interference in the State's peaceful nuclear activities, and in particular in the operation of facilities; and (c) to be consistent with prudent management practices required for the economic and safe conduct of nuclear activities.
INFCIRC/153 Paragraph 6 The Agreement should provide that in implementing safeguards pursuant thereto the Agency shall take full account of technological developments in the field of safeguards, and shall make every effort to ensure optimum cost effectiveness and the application of the principle of safeguarding effectively the flow of nuclear material subject to safeguards under the Agreement by use of instruments and other techniques at certain strategic points to the extent that present or future technology permits. In order to ensure optimum cost effectiveness, use should be made, for example, of such means as: (a) containment as a means of defining material balance areas for accounting purposes; (b) statistical techniques and random sampling in evaluating the flow of nuclear material; and (c) concentration of verification procedures on those stages in the nuclear fuel cycle involving the production, processing, use or storage of nuclear material from which nuclear weapons or other nuclear explosive devices could readily be made, and minimization of verification procedures in respect of other nuclear material, on condition that this does not hamper the Agency in applying safeguards under the Agreement.
INFCIRC/153 Paragraph 9 … The visits and activities of Agency inspectors shall be so arranged as to reduce to a minimum the possible inconvenience and disturbance to the State and to the peaceful nuclear activities inspected ….

2.2 Introduction to IAEA Safeguards Implementation

The IAEA implements safeguards to meet the overall safeguards objective by determining an optimized combination of safeguards measures needed to achieve State-specific technical objectives, based on the evaluation of all available information on the State. The concept of considering the State as a whole provides the opportunity to focus verification efforts and resources where needed to meet the State-specific objectives.

Rather than being static, the IAEA safeguards system is evolving to fulfill its mandate, to better meet safeguards objectives and to address new verification challenges. Consequently, there is no single one-case-fits-all engineering specification is available for designers to consider. This reinforces the importance of the designer working to develop an understanding of safeguards and what the IAEA might want to do, and to engage with the IAEA on these matters while safeguards measures that impact the design, or vice versa, can be addressed at least cost.

The IAEA safeguards system comprises interrelated elements, namely:

- Safeguards agreements and other legal instruments
- Provision of information by States
- IAEA verification activities (e.g. for nuclear material and design information)
- IAEA evaluation of all available safeguards relevant information
- IAEA safeguards conclusions drawn for the State
- Reports on safeguards implementation to States and to IAEA policy making organs (e.g. IAEA Board of Governors, General Conference)

Of the elements listed above, the IAEA verification activities that impact the design of nuclear facilities, or, conversely, are affected by design features, are expected to be of most interest to the design community. However, a general understanding of how the IAEA applies safeguards places those activities in context.

The IAEA and the State Safeguards Regulatory Authority (SRA) should work together to reduce duplication of efforts, minimize errors, avoid miscommunication and implement effective procedures for the submission of information and the conduct of IAEA activities in the field. Technological advancements, such as secure unattended transmission of data from installed equipment, can achieve efficiencies through cooperation.

States must also establish the necessary infrastructure, including requirements, procedures and technical arrangements, to ensure access by IAEA inspectors and technicians and facilitate the receipt and use of their equipment. Likewise, IAEA inspectors and technicians must receive the necessary information and support to carry out their activities under both the CSA and the AP, if applicable. Support may include providing escorts, radiation protection personnel and equipment, technical and operational staff, and training as required.

Upon entry into force of its CSA, a State submits design information on existing facilities during the discussions of the Subsidiary Arrangements, typically within 90 days of entry into force of the CSA. Facility design information is submitted in the form of a design information questionnaire (DIQ). The IAEA examines and verifies the design information to support a number of safeguards activities. The IAEA verifies that facilities are operating in accordance with their stated designs. The IAEA also evaluates the facility, including its function, layout and processes, in order to determine its safeguards approach and the specific measures it will employ to achieve the safeguards objectives. The IAEA determines the specific safeguards measures, and installs and tests safeguards equipment, as required.

DIQ templates for various facility types are available for use by SRAs in submitting preliminary design information. A DIQ should be updated as soon as more detailed information is available regarding the facility. Subsidiary Arrangements to individual national safeguards agreements with the IAEA provide additional information regarding the type of information to provide at each stage in the design and development process. As a DIQ is refined, the IAEA and the State will begin to negotiate the Facility Attachment (FA), which is based on the DIQ. The FA sets out specific details regarding safeguards implementation at the facility, and contains, among other things [1]:

- A short description of the facility
- A provision to submit to the IAEA any changes in the information on the facility
- The accountancy measures to be used at the facility
- Provisions for containment[b] and surveillance measures
- Specific provisions and criteria for the termination of and exemption from safeguards of nuclear material
- A detailed description of the records and reports system
- A description of the mode and scope of IAEA routine inspections
- Provisions for administrative and financial procedures concerning the application of safeguards at the facility

Facility design changes, or changes in the way operations at facilities are conducted, must be evaluated by the IAEA to determine their effect on the safeguards approach. The IAEA may need to make changes to its safeguards measures, which could involve such activities as installing equipment, or relocating cameras. Therefore, this information must be provided to the IAEA well in advance of making the change, specifically, “as soon as the decision to modify the facility has been taken.” This means that SRAs must establish requirements and procedures for facility operators to monitor the design configuration and notify the SRA when considering modifications to the facility operations, in advance of making substantial changes. Substantial changes that require advance notification to the IAEA are specified in the FA and should be submitted to the IAEA as updates to the DIQ.

Typically, plant operators make accountancy declarations of the material balances for their facility, and the IAEA verifies the declaration. The verification measures used by the IAEA include the verification of plant design information, auditing of records and reports, and independent measurements of nuclear materials in the facility. However, safeguards at nuclear facilities are transitioning to a more integrated approach. Integrated safeguards refer to an

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[b] Containment, as used in safeguards, has a meaning different from its normal use by reactor designers. For IAEA safeguards purposes, the containment refers to structural features of a nuclear facility or equipment which permit the IAEA to establish the physical integrity of an area or item by preventing undetected access to, or movement of, nuclear or other material, or interference with the item, IAEA safeguards equipment, or data. Whenever the word ‘containment’ is used by itself (or with modifiers, such as in ‘reactor vessel containment’) in this report, the special safeguards meaning is intended; whenever the term ‘reactor containment’ is used, the system of buildings, structures and isolation devices provided to protect the surroundings of the reactor in the event of an accidental release of radioactive material is intended.

optimized combination of all safeguards measures available to the IAEA under CSAs and APs to achieve maximum effectiveness and efficiency in meeting the IAEA's safeguards obligations within available resources.

In the implementation of safeguards, the IAEA and States each bear their associated costs. However, some costs borne by the State may be reimbursed by the IAEA, should these costs be deemed to be extraordinary and reimbursement has been agreed upon between the IAEA and the State in advance. The Facility Attachment for each facility lists the services and activities for which the IAEA may agree to reimburse costs incurred by the State. States undertake the costs of safe access to facilities on the part of inspectors, including the provision of radiological controls, monitoring and facility-specific training. States that are not members of the IAEA are required to reimburse the IAEA for IAEA costs incurred in the implementation of safeguards.

In order to effectively implement safeguards and comply with its treaty obligations, the IAEA must be able to verify that no diversion of nuclear material from the facility has taken place, and that the facility has not been misused to produce undeclared and unsafeguarded nuclear materials. Towards this goal, the IAEA uses a system of material accountancy complemented by containment and surveillance (C/S) measures to monitor access to, or movements of, nuclear material. The following are important safeguards measures and in-field verification activities used by the IAEA.

2.2.1 Design Information Verification (DIV)

The IAEA utilizes design information to establish the safeguards approach for a specific facility. As such, the IAEA carries out Design Information Verification (DIV) at a facility to verify the correctness and completeness of the design information provided by the State. An initial DIV is performed on a newly built facility to confirm that the as-built facility is as declared. A DIV is performed periodically on existing facilities to confirm the continued validity of the design information and continues to be performed through all phases of the facility's life cycle until the facility has been decommissioned.

The design information verification is on-site verification by the IAEA that the information is complete and correct and satisfies its needs as specified in the safeguards agreement. This verification is performed during a design verification visit, which is not to be confused with the various inspections described elsewhere. The examination and verification of the design information are carried out to:

- Identify those features affecting the application of safeguards. This should be done in sufficient detail to ensure that the safeguards objectives, as laid down in the safeguards agreement, can be met and the IAEA safeguards goals fulfilled
- Determine the Material Balance Areas (MBAs) to be used for IAEA accounting purposes and select Key Measurement Points (KMPs) that will be used to determine the flow and

inventory of the nuclear material. When determining an MBA, the following criteria are taken into account:

  - ⇒ The size of the MBA, which is dependent on the material balance accuracy obtainable
  - ⇒ The use of C/S measures to help ensure the completeness of flow measurements. Advantage should be taken of any opportunity to use these measures. This simplifies the application of safeguards and concentrates measurement efforts at KMPs
  - ⇒ Multiple MBAs at a facility or at defined locations outside facilities, as used by the operator, which may be combined into one MBA if the IAEA determines that this is feasible
  - ⇒ Establishment of a special MBA, at the request of a State, around a process step involving commercially sensitive information

- Establish the nominal timing and procedures for taking physical inventory for IAEA accounting purposes
- Establish the requirements for records and reports and the evaluation procedures
- Establish the requirements and procedures for flow and inventory verification, specifying quantities and identifying the locations of nuclear material
- Select appropriate combinations of C/S methods and techniques and the strategic points at which they are to be applied

Actions to be undertaken by the IAEA in coordination with the SRA before the visit include:

- Examining the design information to establish its completeness (according to the DIQ) and its self-consistency. Determining whether any additional information or clarification that could have an effect on safeguards is needed. Such additional information must be requested formally from the State
- Preparing a preliminary safeguards approach for the facility, based on the design information and any other relevant information available. This draft safeguards approach should take into account specific features of the facility and other relevant features indicated in the safeguards agreement. Important elements are:
  - ⇒ Determination of possible diversion strategies; identification of possible diversion paths; and specification of the detection goals (detection times, significant quantities and detection probabilities) to be achieved for the facility
  - ⇒ Detailed analysis of the identified diversion paths
- Preparing the draft Facility Attachment based upon the model Facility Attachment, the design information, the goals and procedures and any other relevant facility information
- Planning the on-site verification activities

Features of the facility that are of special interest include:

- Containment features
- The flow of material, its type and its physical and chemical form

- Possible identification methods of items and batches
- The measurement methods used and their accuracy
- Sampling procedures and methods for ensuring the integrity of samples
- Methods of storage and containment of material from the viewpoint of measurement techniques used by the IAEA
- Recording and reporting procedures
- Possibilities of using C/S equipment

An advanced tool developed for use in DIV is the 3-D laser-based DIV tool shown in Figure 2-1. With such tools IAEA inspectors can accurately verify the facility is as designed. Figure 2-2 illustrates how changes in the facility can be detected with DIV instruments.

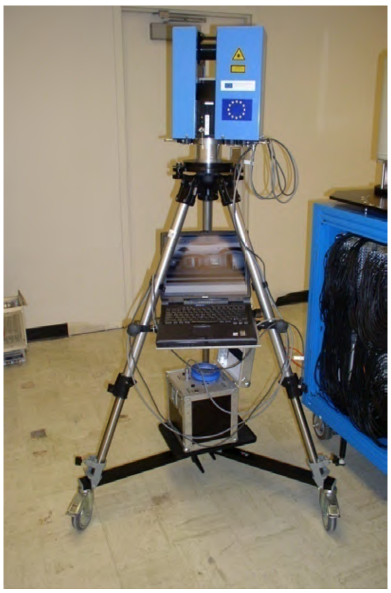

Figure 2-1
3DLRFD laser DIV tool

Figure 2-2
Sequence of images illustrating changes in facility configuration which would be identified by DIV equipment. The image on the left is the reference image; the center

image is the new image; and the right image highlights in red objects that have shifted position beyond a set tolerance level

2.2.2 Nuclear Material Accountancy (NMA)

The purpose of the nuclear material accountancy system is to establish the quantities and locations of the nuclear material present in a nuclear facility and the changes that take place in these quantities and locations. Nuclear reactor facilities are considered as a single material balance area (MBA) with a number of key measurement points (KMPs), through which material is transferred or where it is stored or used.

Figure 2-3
Inspectors conducting nuclear material accountancy verification

The essential elements of such an accounting system and the associated inspection procedure are that:

- The operator identifies, counts or measures the nuclear material in the facility and maintains inventory records
- The operator keeps a record of all use and production of nuclear material, and of transfers into and out of the facility, i.e. of all the inventory changes
- The operator prepares reports on the inventory and its changes and submits these reports to the IAEA through the appropriate State body responsible for safeguards
- IAEA inspectors visit the facility to verify the inventories and inventory changes, to determine the validity of the operator's accounting system and the correctness of the reports made to the IAEA. Verification of the inventories and inventory changes includes on the spot identification or measurement of the material (See Figure 2-3). The inspectors also review

the information from surveillance and radiation equipment installed at the facility to determine if the surveillance and radiation results are consistent with the operator's records

2.2.3 NDA Measurements

Non-destructive assay (NDA) is used by the IAEA as a part of nuclear material accountancy and to verify the correctness of records and reports submitted by a State. NDA is the measurement of nuclear material content or isotopic concentration of an item without producing any physical or chemical changes in the item. NDA measurement techniques employ either passive or active analysis. The IAEA uses both portable NDA instruments and unattended NDA equipment installed at KMPs to measure declared nuclear material and to detect undeclared movement of nuclear material.

Gamma-ray measurements are often used by inspectors to identify nuclear material and its quantity. The HM-5 portable NDA probe shown in Figure 2-4 is easy to use and provides initial indications of nuclear materials. The InSpector-2000 multi-channel analyzer system shown in Figure 2-5 is more robust and provides better measurements than the HM-5, but requires more effort to implement than the HM-5. For conducting measurements of spent fuel, fork detectors (FDETs) and spent fuel attribute testers (SFATs) are used (see Figure 2-6 and Figure 2-7, respectively). Other instruments are also used by IAEA inspectors, but the below pictures give an idea of the types of equipment to be expected. For the NPP designer, these sorts of instruments should be kept in mind when considering access for such IAEA equipment in MBAs and spent fuel areas of the NPP.

Figure 2-4
HM-5 hand-held assay probe with NaI detector for identifying nuclear and other radioactive materials

Figure 2-5
InSpector-2000 multichannel analyzer with germanium detector for isotopic analysis of uranium enrichment and plutonium isotopes

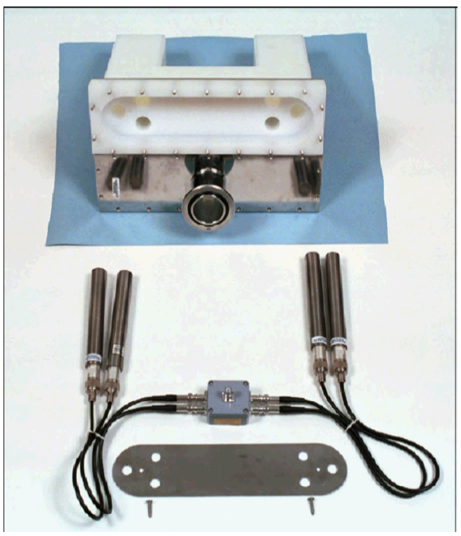

Figure 2-6
Fork detector for verifying spent fuel burnup

Figure 2-7
Spent fuel attribute tester to verify presence or absence of cesium-137

2.2.4 Containment/Surveillance

Containment/ surveillance (C/S) is the primary method for the IAEA to ensure the Continuity of Knowledge (CoK) of nuclear material in order to detect efforts to compromise the safeguards relevant properties of an item containing nuclear material. During inspections IAEA inspectors examine the C/S systems, i.e. containments, seals, and surveillance results, as part of verifying operator records and reports. Containment refers to the structural features of a facility or of equipment (e.g., seals, see **Figure 2-8**) which permit the IAEA to establish the physical integrity of an area or item by detecting access to, or movement of nuclear or other material, or interference with the item, IAEA safeguards equipment, or data. Sealing systems are used to cover spent fuel inventories stored in spent fuel pools, spent fuel casks, the reactor core, and transfer gate canals.

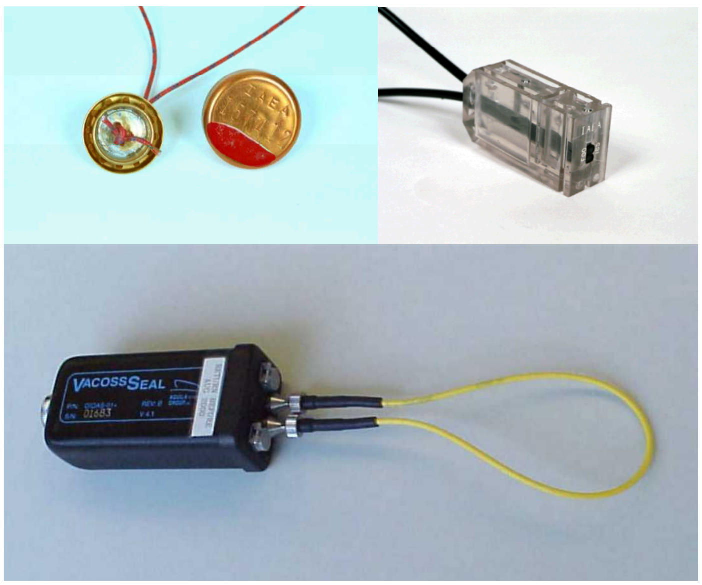

Figure 2-8
Seals used by the IAEA to assure no tampering has occurred. Upper left image is a Type-E metal seal; Upper right image is a Cobra seal including its seal body and associated fiber optic cable; and lower image is a VACOSS seal and its fiber optic cable

Containment refers to the structural components that make access difficult. Containment is used to control access to nuclear material, equipment and data. Seals are tamper-indicating-devices used to secure penetrations in the containment. Surveillance is the collection of optical or radiation information through human and instrument observation/monitoring. The IAEA has several cameras systems approved for use [17] that:

- store data
- include local battery backup
- provide state-of-health or picture data to an off-site location
- can be triggered by other sensors

- can be sealed in tamper indicating enclosures

At reactor facilities a safeguards surveillance camera system is installed to view the spent fuel storage areas, the spent fuel pool, spent fuel transfer routes, and the reactor pressure vessel when it is open for refueling. Surveillance is used to detect and/or confirm:

- all movements of nuclear materials
- the intact condition of all material or containment of material
- the validity of information related to locations and quantities
- the integrity of any IAEA seals and equipment
- the absence of undeclared operations

Digital camera systems are often used by the IAEA. Shown in **Figure 2-9** is a single-camera system typically used where physical access within the facility is difficult. Shown in **Figure 2-10** is a multi-camera system. Note the much larger footprint required by the electronics and power systems. Such multi-camera systems require cabling access from the electronics cart to the various camera positions, and the electronic cart itself requires a dedicated area within the facility, preferably in a special room accessible only by IAEA personnel.

Figure 2-9
Digital Single-camera Optical Surveillance (DSOS) system for single camera applications where it is difficult to access the camera position

Figure 2-10
Digital Multi-camera Optical Surveillance (DMOS) system for remote monitoring and unattended monitoring applications in complex facilities requiring multiple (up to 16) cameras

2.2.5 Unattended and Remote Monitoring

One way to achieve optimization of resources is with continuous unattended surveillance and radiation monitoring systems that are remotely accessed by IAEA inspectors. By using this approach on-site inspector time can be reduced without compromising safeguards. In a reactor facility, monitoring stations established at key parts of the facility, such as in fuel transfer chambers, with data transmission and remote accessibility by the IAEA are a key component of integrated safeguards. Integration of this type of monitoring into the facility requires close coordination between the IAEA and the design team.

Unattended monitoring is a special mode of application of non-destructive assay or C/S measures, or a combination of these, which operates for extended periods without inspector intervention. The use of unattended safeguards instruments has long been a part of IAEA safeguards. Optical surveillance used to monitor an area for safeguards relevant activities over extended periods is unattended. Unattended radiation detection sensors are used to monitor the flow of nuclear material in a facility process area. For unattended monitoring, certain criteria must be met, including measures to ensure data authentication and encryption.

Remote monitoring is a technique used to transmit data from unattended C/S, monitoring, and measurement systems off-site via secure communication networks to IAEA Headquarters, a regional office, or other IAEA location for review and evaluation. The system's internal recording capability is used for backup purposes. Remote monitoring may provide better utilization of equipment, better planning of inspections and a reduction in the inspection effort needed to meet verification requirements. These systems transmit data ranging from equipment state of health data to verification data. The use of redundancy is particularly applicable for unattended C/S and monitoring devices. For data sent over unsecured transmission lines, authentication and encryption are required. Accommodating remote monitoring systems early in facility design would be one area in particular where SBD could offer benefits to all parties.

2.2.6 Facility Physical Infrastructure Needs for IAEA Safeguards Activities

The basic needs of IAEA safeguards equipment include physical space, mains power, and a data transmission backbone (wired or wireless).

Figure 2-11
Installation of surveillance system (IAEA photograph 03210021)

Figure 2-11 illustrates a surveillance camera installation that might require access by more than one person (e.g., including the facility operator escort), dedicated physical space, electrical power and either local or nearby data archive capability. Even without detailed IAEA design criteria for safeguards equipment or systems, the ability to provide access to stable reliable power and to data transmission capability throughout a nuclear facility would address some of the most costly aspects of retrofitting for safeguards equipment systems and allow flexibility for future safeguards technology installation [18]. One might refer to these most basic needs as the minimum safeguards equipment infrastructure set. Safeguards technologies continue to evolve, as does nuclear technology. An ability to easily upgrade systems is dependent on the flexibility of the facility infrastructure design. Figure 2-12 shows 20 years of development in support electronics for a type of neutron measurement instrument. A facility design that accommodates modest changes in equipment size, shape and power requirements allows the use of newer alternatives as they become available on the market or as obsolescence removes older alternatives. Reference [19] includes information about the functions, size and infrastructure requirements of IAEA equipment.

Figure 2-12
Evolution of shift register electronics for neutron measurements (LANL photograph archive)

3

STAKEHOLDER INTERACTION

SBD involves early stakeholder interaction, which is vital for the effective implementation of safeguards. In addition to the IAEA, five such stakeholder participants are designers, vendors, project managers, operators and safeguards competent authorities.

Designers and Vendors

Designers and vendors have the responsibility for understanding the many requirements relating to safeguards, security, and safety as well as the operational requirements. These requirements can include detailed information about safeguards activities, e.g. those that require access, instrumentation that must be installed or any physical infrastructure in the facility necessary to support the safeguards equipment. Safeguards expertise should be included in the design team, and experience shows that an expert on IAEA safeguards, working with subject matter experts from various other components of the design team, can quickly identify any new safeguards challenges posed by the design, and possible design or safeguards steps that can mitigate those challenges. [2], [24]

Project Management

The project management has the responsibility for managing the competing interests, bringing the design/construction project to a successful conclusion and, ultimately, delivering a quality facility ready to operate. It is recommended that project managers understand enough about safeguards to make informed decisions about safeguards.

Operators

Operators have the responsibility for facility operations, communication between the facility and the relevant State, regional and IAEA safeguards authorities, and implementing nuclear material accountancy and safeguards at the facility level. Operators can benefit from understanding the safeguards system and can have personnel and equipment dedicated to either or both national and international safeguards activities.

State or Regional Safeguards [Regulatory] Authority (SRA, RSRA)[c]

The safeguards authority (e.g. the Nuclear Regulatory Commission in the U.S.) has the responsibility for fulfilling the obligations of the State as defined by treaties and agreements, including formal communications with the IAEA. Direct communication between stakeholders such as designers, vendors, operators and the IAEA can be arranged and approved by the safeguards authority.

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[c] In common safeguards usage, the term SRA refers to the authority responsible for safeguards implementation in the State, which may involve more than one entity in the government, a regional entity, or a combination. In some States, the authority for safeguards does not include regulatory authority.

3.1 Safeguards Concerns at Stages of Design

Each phase in the life-cycle of the facility can benefit from consideration of safeguards where safeguards equipment needs to be designed, monitored, installed, maintained, and upgraded. While safeguards implementation potentially has a small impact on project cost and schedule when considered early in the design process, failure to do so can result in a much larger impact than necessary both in construction and during operation. **Figure 3-1** depicts the stages of design in a simplified form, and potential SBD implementation at each stage is discussed below. The safeguards authority is the official contact with the IAEA and should generally be included in the safeguards dialogue as a stakeholder or as an observer, as appropriate. When the designer and the operator are from different States, each may report to a different safeguards authority. Once a location in a State is selected for the nuclear facility, the corresponding safeguards authority will be the official contact with the IAEA.

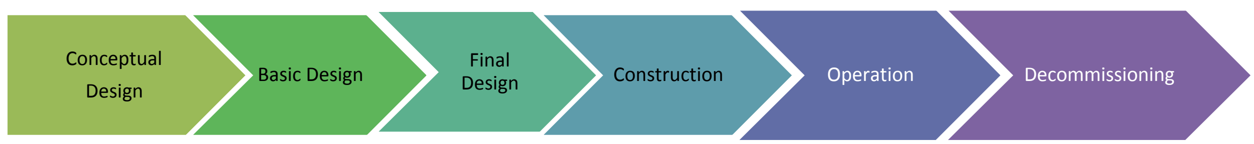

Figure 3-1
Facility design stages

Conceptual design — the project planning period, the earliest design stage where a preliminary conceptual safeguards system might be laid out.

- Designer/operator can work with the safeguards authority to ensure that the IAEA is aware of the design and can begin engagement
- The IAEA can perform an evaluation of the operational process
- The IAEA suggests preliminary considerations for a safeguards approach and negotiations begin
- Designer/operator/IAEA can identify potential safeguards risks in the conceptual design

Basic design — subsystem designs under way, basic facility design details are available, including proposed safeguards equipment and locations.

- The IAEA can make a preliminary definition of MBAs and KMPs
- All can consider how the design can be optimized to meet safeguards goals
- Designer can assess if the design supports the physical infrastructure necessary for safeguards systems and equipment
- An analysis[d] can be performed to verify that no unmonitored opportunities for diversion or misuse exist

[d] Terms such as diversion/acquisition path analysis have been used to label such an analysis

Final design — detailed facility design complete, dimensions, equipment and planned operations are known, allowing for confirmation that the various systems will meet specified requirements with the minimum interference between systems.

- Stakeholders review detailed facility design
- Stakeholders confirm safeguards system design can meet requirements

Construction — the facility is constructed according to the specifications. When the facility design or safeguards system are changed during construction, the changes can be assessed to ensure that they have not compromised the safeguards system. The IAEA:

- reviews as-built status
- confirms that safeguards system design meets requirements

Operation — the operator starts up the facility and systems testing is under way. The IAEA confirms that:

- as-built documentation exists for DIV and safeguards system
- the safeguards system operation meets requirements

Decommissioning — the operator takes the facility out of operation and begins dismantlement. The IAEA:

- verifies the removal of nuclear material
- confirms the removal of essential equipment
- terminates safeguards on the facility

3.2 Project Life Cycle Cost Evolution

Large design-and-construction projects must address a wide variety of regulatory and operational requirements. Typically, large projects endeavor to reduce retrofits and to eliminate defects from the design earlier rather than later in the design and construction process in order to minimize the impact of change. The cost of removing defects is lower before design features have been finalized. Figure 3-2 below illustrates how early consideration of requirements can reduce total project costs in large projects.[e] It indicates that the costs of removing defects once the facility is operating are even higher that those incurred late in the design and construction process.

[e] INCOSE, 2007, Systems Engineering Handbook – A Guide for System Life Cycle Processes and Activities, Version 3.1, http://www.incose.org/ProductsPubs/incosestore.aspx

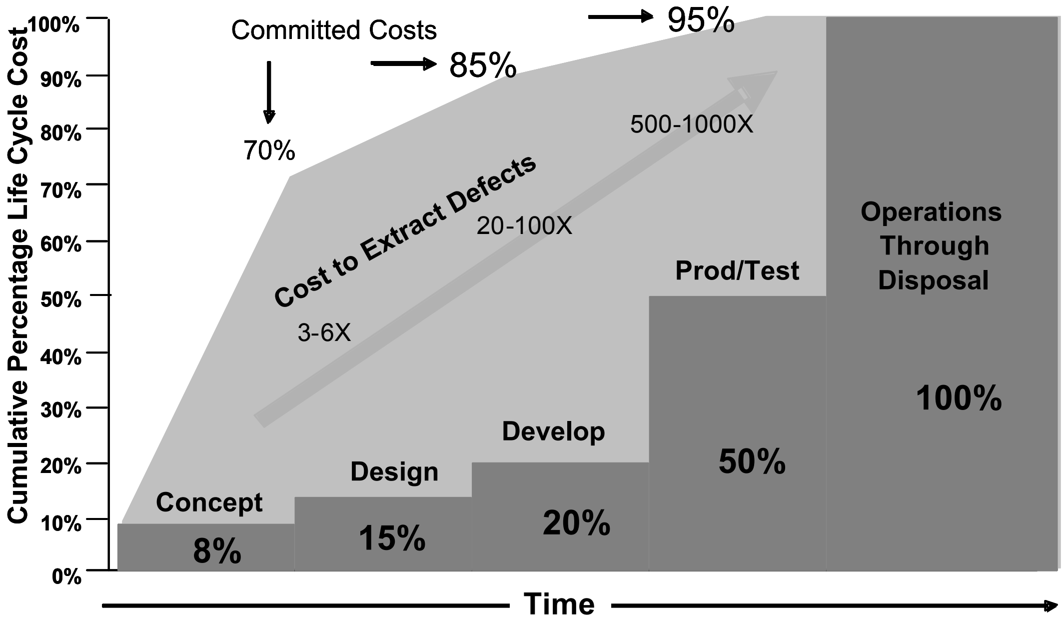

Figure 3-2
Cumulative life cycle costs as function of time

4 SAFEGUARDS CONSIDERATIONS RELATED TO REACTOR DESIGN

In this section, the term 'IAEA safeguards equipment' will be used frequently to represent various lists of equipment. It does not correspond to a single list. This section uses an LWR fueled with low enriched uranium (LEU) as a baseline example. References [1] and [20] give additional information. Much of the baseline guidance can apply to any reactor type, and additional points addressing reactor variations are discussed in section 5.

In the conceptual design step, international safeguards can be considered by way of general guidance that is not overly prescriptive. Guidance that describes the safeguards issues, rather than prescribes how to address them, may be more readily used by the facility designers and operators at this stage. Dictating specific technology solutions for facility safeguards can be challenging due to the variability in facility designs that preclude 'one-size-fits-all' solutions. However, dialogue about safeguards considerations can usefully include descriptions of metrics for accuracy, precision, and validation of results.

For example, while it is not feasible to identify an exact camera location until parts of the design are fixed, it is feasible to let the designer know a camera needs adequate illumination and which activities involving the reactor core a camera will be used to monitor when the reactor is being refuelled. The designer can also consider the surveillance requirements as the layout and design are optimized. Specifications for the frequency of picture taking, the supply of electrical power, the space, and communications cabling can be discussed without knowing the exact location or height above the working level(s) of the final installation.

A designer can keep general safeguards considerations in mind, such as:

- how to facilitate inspection activities
- how to minimize the need for IAEA inspectors to revisit the site for clarification of information collected during previous visits
- how to mitigate safeguards issues during off-normal events
- where to install backup or emergency power and for how long

Measures that can facilitate inspection activities include:

- providing access to and space for safeguards equipment maintenance[f]
- minimizing radiation exposure of inspectors (and equipment)
- providing access to and space for design verification (e.g. containment and piping)
- minimizing potential for damage to safeguards equipment or loss of safeguards data
- providing adequate illumination for personnel access and for surveillance equipment

[f] Each State has building codes with recommendations for ingress/egress and working space to access junction boxes and electrical cabinets.

- clearly labelling safeguards equipment and its physical infrastructure[g]
- providing unique identifiers for nuclear material items
- providing reliable, low-maintenance equipment

The greatest technical challenge for safeguarding a reactor concerns direct use material. Any unirradiated[h] HEU or plutonium will have the shortest timeliness goal (traditionally one month) and a smaller SQ. Misuse of the reactor to produce irradiated direct use material can be hard to detect. Irradiated fuel traditionally has a three-month timeliness goal (once in-growth of the fission products reaches a moderate level) while fresh LEU fuel has a one-year timeliness goal. Also of interest is whether the facility has pin replacement capability, since opening a fuel assembly to remove or replace a pin destroys the item integrity of the fuel assembly.

In a reactor facility the nuclear material comes into the reactor as fresh fuel, is used in the core to provide energy (fuel can be shuffled in the core to optimize burnup), moved to short term storage, and then shipped to long term storage or away from the reactor facility. While the core is operating, the nuclear material items inside the core are transformed and plutonium is produced (assuming LEU fuel). It is not easy to calculate the new isotopic or spatial distributions of the used fuel accurately, and it is even more difficult to measure these characteristics accurately.

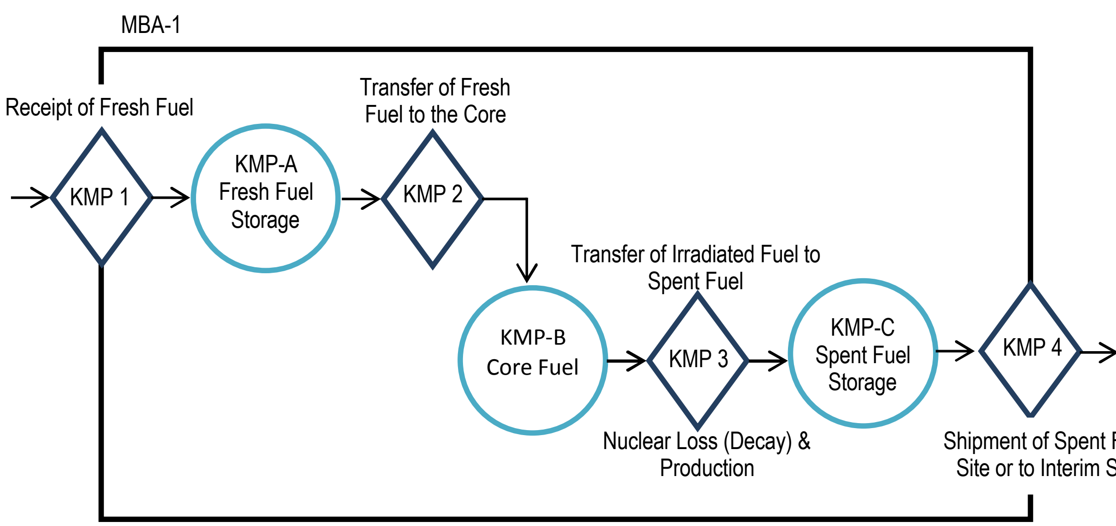

Figure 4-1
Material balance area and key measurement points for an LWR

Inventory KMPs are generally located at the fuel storage areas: (a) fresh fuel storage, (b) reactor core, and (c) reactor spent fuel storage; and flow KMPs at fuel transfer sites: (i) fresh fuel receipts, (ii) fuel transfers from fresh fuel storage to the reactor core, (iii) irradiated fuel transfer from the reactor core to spent fuel, (iv) transfer of recirculating core fuel, (v) transfer of spent fuel to storage, and (vi) spent fuel transfer/shipment from the MBA/facility. Figure 4-1 depicts a

[g] The IAEA's working language is English.
[h] For safeguards purposes, unirradiated implies the absence of fission products, not whether the nuclear material itself has been irradiated.

simplified MBA and KMP layout for an LWR, including four flow KMPs and three inventory KMPs (labelled A, B, C).

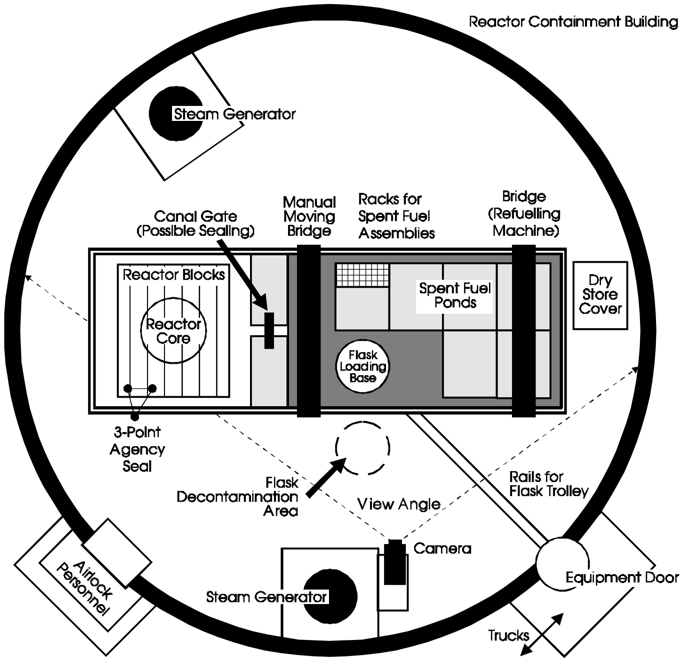

Figure 4-2
Traditional safeguards C/S equipment for type I reactor

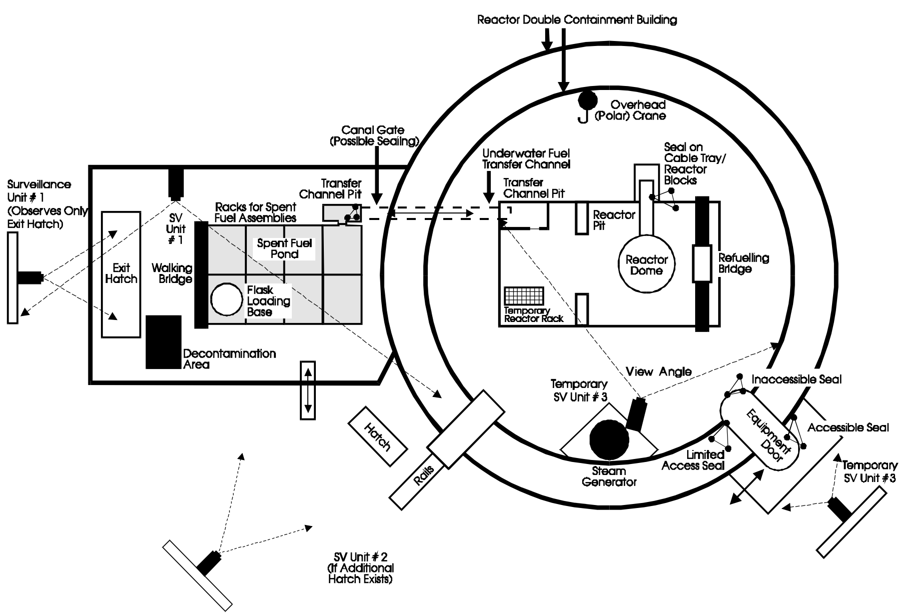

Figure 4-3
Traditional safeguards C/S equipment for type II reactor (SV=surveillance)

The safeguards approach at a power reactor includes C/S measures. A traditional safeguards C/S approach is shown in Figure 4-2 and Figure 4-3. Figure 4-2 shows a type I reactor (the spent fuel pond is inside the reactor containment) and Figure 4-3 illustrates a type II reactor (the spent fuel pond is outside the reactor containment). In these illustrations of C/S equipment, surveillance cameras and tamper-indicating seals are positioned to view areas or activities of potential safeguards interest, some within the containment. Safeguards equipment can include:

- cameras in the reactor hall, above the fuel ponds, and monitoring core activities
- seals on containment penetrations, important fuel transfer channels
- NDA measurements of fresh and irradiated fuel, with different equipment

Actual locations and the numbers of units and seals are determined for each site according to the specific design. A designer can potentially consider the safeguards C/S needs and also any measurement equipment needs as part of the design optimization process.

For existing designs with a well-known safeguards approach, lessons learned from implementation and operation of the safeguards equipment can be useful input for consideration in subsequent plants to be constructed.

4.1 Misuse/Diversion Scenarios

For existing designs in current operation, the misuse/diversion scenarios have been addressed with the safeguards approaches. Re-investigation by the design team is not expected to be cost-effective. However, a basic understanding of current practice might be useful to the design team.

For innovative designs, designers can perform an analysis, possibly in collaboration with safeguards authorities and the IAEA, to identify possible misuse and diversion scenarios. Appendix B and references [21] and [22] discuss methods for in-depth analysis.

There are two basic misuse/diversion scenarios for nuclear reactor fuel: (i) the diversion from declared inventory and (ii) undeclared production. Misuse involves production of undeclared nuclear material (typically from irradiation targets in a reactor), i.e. the IAEA has not been informed of it.

It might be helpful in the implementation of safeguards for designers to become familiar with the concept of diversion and misuse scenarios and the related pathways that safeguards are intended to address. Designers can consider all types of diversion, including abrupt diversion, protracted diversion, and misuse followed by diversion. Some examples of possible misuse/diversion scenarios and potential safeguards measures to address the scenarios are described in Table 4-1.

Practical examples of design features to help make diversion more difficult are discussed in following sections and include:

- easy-to-read, unique identifiers for nuclear material items
- minimal number of penetrations in the containment structure
- layout of the facility to minimize the need for multiple surveillance systems

- features to easily distinguish fuel and non-fuel items
- access controlled spaces for receipts, storage, and measurement of nuclear items

Table 4-1
Diversion Strategies

Diversion possibilities	**Concealment methods**	**Safeguards measures**
Removal of fuel rods or assemblies from the fresh fuel storage area	Substitution with dummies, falsifying records, borrowing	Item counting, item identification, application of seals, NDA measurements, simultaneous inspections
Removal of fuel assemblies from the core	Substitution with dummies, falsifying records, borrowing	Item counting, item identification, seals, optical surveillance, spent fuel bundle counters, core discharge monitors, simultaneous inspections
Irradiation of undeclared fuel assemblies or other material in or near the core, and removal of the material from the facility	Undeclared design changes allowing targets to be introduced into the core	Seals, optical surveillance, NDA measurements, spent fuel bundle counters, core discharge monitors, power monitoring, design information verification
Removal of fuel rods or assemblies from the spent fuel pool	Substitution with dummies, falsifying records, borrowing	Item counting, item identification, seals, optical surveillance, NDA measurements, spent fuel bundle counters, simultaneous inspections
Removal of fuel rods or assemblies from a consignment when or after they leave the facility	Substitution with dummies in the consignment, understating the number of assemblies shipped and substitution with dummies in the spent fuel pool	Verification of content of shipping container, sealing of shipping container before shipment, and verification of content at receiving facility

4.2 General Guidance

With an understanding of IAEA safeguards objectives and the tools and measures of the inspectorate, some general guidance to consider would be:

- to provide infrastructure support (e.g. normal and backup power, lighting for surveillance, access, dedicated space, data transmission) inside the facility. Figure 4-4 shows the operator providing installation support during emplacement of IAEA equipment
- if a video surveillance or fuel flow monitoring system is used that requires a data collection cabinet, to install the cabinet in an area/room protected from extreme temperature, humidity, and dust
- to minimize the number of access points in the reactor containment and other shielding structures through which any fresh or spent fuel movement can take place
- to design for adequate uninterruptible electrical power to support safeguards equipment and instrumentation (e.g. instrument cabinet, instrument sensors, IAEA installed or facility illumination, cooling-heating) with battery/diesel generator/gas turbine backup for unattended systems
- to plan the fuel transport routes so that C/S and nuclear material flow monitoring systems have the ability to clearly distinguish between routine fuel transfers and other fuel activities, and also between fuel and non-fuel activities
- to ensure that optical surveillance systems are not blocked by large pieces of equipment (e.g. the fuel handling crane)

Figure 4-4
Installation of IAEA equipment racks[i]

[i] IAEA photograph archive

- to consider penetrations through containment (e.g. the reactor safety containment) for cabling for safeguards equipment to avoid situations where penetrations have to be drilled in later during construction
- to provide 0.5 m^2 access for attaching, replacing, or servicing any seals
- to minimize the effect of safeguards on plant operation by designing locations for safeguards equipment that are accessible for inspection, monitoring, and maintenance and that do not obstruct or impede plant operations
- to ensure that inspectors can accomplish all safeguards activities safely and expeditiously and that safeguards equipment is reasonably protected from unintentional damage
- to consider provisions protecting proprietary and restricted information. Establish specific IAEA inspection routes, methods for shrouding, or physical barriers for managed access
- to label all installed relevant safeguards equipment (including cabling power supplies and switches) clearly to avoid inadvertent interruptions in surveillance and monitoring
- to provide capabilities to enable the use of safeguards seals at KMPs and safeguards relevant features like key junction boxes where cables are terminated or connected
- to ensure verification of spent fuel in storage without undue handling. Ease of verification can include unattended monitoring for fuel movement, C/S of IAEA equipment inside of containment[j], and provisions for sealing of the storage to reduce the need to reverify fuel assemblies and/or rods
- provide a single dedicated space for the safeguards' electronic equipment[k] that can be access controlled by the inspectorate. this space might include additional room for future technologies that can expedite safeguards' activities
- minimize the impact on facility operations from inspector measurements by considering controlled space, access control, and access to facility infrastructure (e.g. cranes, bridge over pool) for any required verification measurements
- provide means to mitigate the consequences to safeguards continuity of knowledge from off-normal events.

4.3 Specific Locations within Reactor

Nuclear material at a reactor is present in four areas: the shipping/receiving area, fresh/spent fuel storage, the core, and in fuel transfer chambers. Each area warrants specific consideration.

4.3.1 Shipping/Receiving

Typically, a nuclear power reactor receives fresh fuel and ships spent fuel. Usually the nuclear material arrives inside sealed transport casks. The transport containers might remain in this area, possibly under surveillance, until an inspector is available to cut the seal and allow the transfer of

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[j] For example, some equipment used while on-load reactors are at power is inside the containment under seal.

[k] Some safeguards equipment has dedicated electronics racks for signal processing, batteries, and a data archive located remotely from the sensor in less hazardous space than the sensor requires.

the assemblies to the fresh fuel storage[1]. The safeguards relevant activities to be performed upon transfer to the fresh fuel storage are the following:

- The inspector detaches the seal from the transport container
- The operator unloads the transport containers and transfers the fresh fuel assemblies into the fresh fuel storage

When spent fuel assemblies leave the nuclear facility, the safeguards relevant activities to be performed depend on the legal arrangements. Usually the transport container is loaded in the spent fuel pond area, where inspectors will identify each fuel assembly and perform appropriate NDA measurements on each assembly. Once the transport container is full, it is closed and the inspector seals it. The transport container is then moved to the shipping area where it will stay under surveillance (usually provided by cameras) until shipment. The shipment itself does not necessarily require the presence of the inspector.

In the shipping area, if the nuclear material is still on site during routine inspections, the inspector can verify the seal on the transport container and review the surveillance data. Otherwise only the surveillance data can be reviewed.

Design features for the shipping/receiving area of the facility that will assist in the implementation of safeguards include a minimum number of access points in the shipping/receiving area, with suitable arrangements to allow for NDA, sealing, and/or surveillance equipment of access points.

4.3.2 Fresh/Spent Fuel Storage

Fresh fuel storage could be either dry or wet. The radiological hazard related to LWR fresh fuel assemblies is low and no particular biological shielding is needed, making the items easily accessible to inspectors. Typical activities performed in this area during inspections are item counting, identification and NDA measurements for gross defect verification according to a sampling plan. The fresh fuel storage might be under optical surveillance for ensuring continuity of knowledge. Sometimes it might be necessary to seal part of the fresh fuel inventory. Information needed by the inspectorate is a list of the available items in the storage, an updated map of the storage including the identification of the items, their position in the storage, and their content in nuclear material categories.

If the storage is aqueous, some of the NDA measurements will require placing equipment in the water during the inspection. This aspect needs to be taken into account by both the design of the system and the facility's decontamination health and safety regulations and procedures.

From a safeguards point of view, it would be convenient to design the system and to schedule operations in the fresh fuel area in order to minimize unnecessary access and activities, including minimization of off-site shipments and receipts.

[1] The cutting activity might occur during a routine inspection or the inspectorate might arrange to send an inspector on site upon the arrival of the transport container.

The design features for fresh fuel storage areas that assist in implementing safeguards are:

- a minimum number of access points to the fresh fuel storage area, with suitable arrangements to allow for sealing/surveillance
- a layout of the fresh fuel storage that allows inspectors to verify and progressively seal groups of fuel assemblies as they are put into storage without affecting the continuity of knowledge of the fuel already in inventory
- adequate space and illumination between assemblies that allow inspectors to read the identifiers on fuel assemblies and conduct NDA, specifically:
  - ⇒ provision for the use of the inspector's portable NDA equipment
  - ⇒ arrangement of fuel within the storage area to minimize the necessity for moving fuel to identify specific assemblies

LWR spent fuel is stored in spent fuel ponds to provide both cooling and biological shielding. In addition, the inspectors carry out routine verification activities, which can be item counting, item identification, measurements with a Cerenkov viewing device (ICVD or DCVD) and/or random gamma measurements [17]. Figure 17 shows an IAEA inspection using the reactor hall bridge crane with a Cerenkov viewing device to observe irradiated fuel. The area can be under optical surveillance, and the transfer channels between the core and the pond can be sealed.

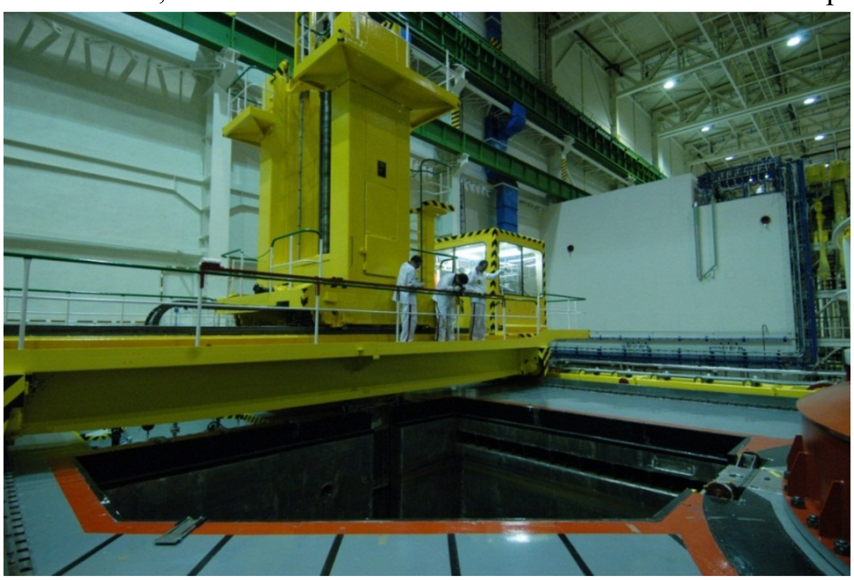

Figure 4-5
PIV of irradiated fuel using Cerenkov instrument[m]

During routine inspections surveillance data is reviewed on site or collected for review and any seals are checked. Some design features for spent fuel storage areas relevant to safeguards are that:

- some of the NDA measurements can require plunging equipment in the water during the inspection; this aspect can be taken into account in the design of the system

[m] IAEA photograph 03210036

- the analysis of the Cerenkov glow emitted by every assembly in the pond can require the inspector to be able to position him/herself over each irradiated assembly, on a vertical axis to the assembly to be verified
- limiting access and activities in nuclear material storage or handling areas can facilitate IAEA review of C/S data by reducing opportunities to observe difficult to understand data

Design features for spent fuel storage areas that assist in the implementation of safeguards are:

- a location that provides an unobstructed view of activities potentially involving nuclear material that is suitable for the installation of surveillance equipment
- light sources in the room whose spectrum does not overlap with the characteristics of Cerenkov glow detection techniques
- storage racks, preferably configured in a single layer, that permit viewing directly from above the top of each fuel assembly with its identifier visible (e.g. no overhang over fuel storage locations to block the view)
- provisions for verifying and sealing the fuel in the lower layer(s) if fuel storage is in more than one layer
- an indexing system such that the inspectors can identify specific fuel assembly locations from the fuel handling control point
- a minimum number of openings in the building structure through which it is possible to transfer spent fuel, with suitable arrangements to allow for their sealing/surveillance
- water clarity and surface stability that allow easy visual inspection of the fuel assemblies in their storage position and viewing of the Cerenkov glow from the assemblies. The Cerenkov glow requires water clarity in both the ultraviolet and visible light spectrums. Figure 4-6 is a close-up of inspectors using a Cerenkov viewing device directly above the spent fuel assembly

Figure 4-6
Inspector viewing irradiated fuel assemblies using Cerenkov glow viewing device[n]

- a spent fuel cooling water return route designed so as to prevent thermal turbulence near surface of fuel assemblies
- provisions that facilitate the annual physical inventory verification that consists of counting the total number of spent fuel items and verifying spent fuel attributes by NDA, specifically:
  - ⇒ minimizing the movement of fuel for counting and measurement purposes
  - ⇒ providing adequate working space on the bridge for inspectors and equipment (e.g. FORK, ICVD or DCVD) as illustrated in Figure 4-5 and Figure 4-6 above
  - ⇒ for special cases (e.g. long-cooled fuel, low burn-up fuel or locations not vertically accessible), providing for the raising or quarantine of assemblies chosen for sampling to allow NDA by the inspector’s equipment
  - ⇒ providing configuration in the facility design for the fuel handling process and storage that facilitates the verification of fuel transfers out of the spent fuel pool (e.g. using remote monitoring)
  - ⇒ designing a location that facilitates safeguards during fuel reconstitution such that, if possible, the flow of assemblies/rods into and out of the area follows predefined routes monitored by IAEA equipment
- provisions for inspection of any closed containers located within the spent fuel pool
- limited space for shielded containers or undeclared transfer flask/cask
- a hoist for a portable underwater camera used to item count and item identify spend fuel in the spent fuel pool or spent fuel cask
- a minimum number of personnel access points into area
- underwater storage locations for safeguards equipment used underwater

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[n] IAEA photograph 03210038

Interim spent fuel storage installations, which typically include a dry storage facility on the nuclear power plant site, can also benefit from SBD. Since such storage areas are increasingly implemented at nuclear power plants, they need to be considered in the overall safeguards approach for a given reactor site. Industry can, therefore, be aware of the relevant safeguards requirements and, where possible, accommodate them in facility designs.

4.3.3 Core

In off-load reactors the core is usually sealed[o] for the entire irradiation period, and the core can be kept under optical surveillance. Prior to refuelling, the inspector might install a backup temporary surveillance camera. When refuelling takes place, inspectors might be present and perform core verification (item counting, gross defect verification via Cerenkov glow evaluation, and if possible item identification). After the closure of the core, the inspector seals it with an IAEA seal.

As with Cerenkov glow evaluation in the spent fuel pond, the inspector needs to be able to position him/herself in a perfect vertical alignment with every assembly in the core. The system's design should enable this.

The design features for the reactor core that assist in the implementation of safeguards are:

- a sealing system for the nuclear material within the reactor core. Such a system can be accessible for inspection, easy to install, and protected against damage. The preferred core seals are usually indirect in that they are multi-point seals applied to the missile shield, the reactor slab, or some other component, rather than directly to the reactor vessel (the attachment points for the seal wire cannot be removable without breaking the wire)
- surveillance equipment for viewing reactor vessel operations whenever the vessel is open
- underwater illumination in the reactor vessel and sufficient water clarity so that the inspector can count the fuel assemblies, read their identifiers, and use Cerenkov viewing devices
- provisions that allow the IAEA to implement power monitoring in small reactors

In general, the IAEA places a minimum amount of equipment inside the containment (typically the sensor might be inside but support electronics are outside) because access for maintenance and to retrieve data is much easier. For example, a surveillance camera inside the containment can be connected to support or data storage equipment located outside the containment.

4.3.4 Fuel Transfer Chambers

Design features for the fuel loading and unloading area that assist in the implementation of safeguards are:

- a suitable mounting for surveillance equipment that inspectors can use to view identifier numbers of fuel assemblies when the transfer canals are being used for refuelling operations

[o] A possible sealing arrangement foresees two seals: a copper-brass one and an electronic one.

- an indexing mechanism on the refuelling machine with a device which can identify the location of each assembly
- a provision for sealing the canal gate (when applicable) to indicate to the inspectors when it is open, and an indexing system (where possible) to monitor material shipments between the core and spent fuel pool
- a provision for inspector access over fuel loaded into casks or underwater cameras to verify spent fuel identifiers
- installation of NDA equipment at KMPs between the reactor core and spent fuel pool
- a surveillance/NDA system to maintain continuity of knowledge over verified spent fuel

4.4 Decommissioning

In the context of international safeguards, a facility is considered as decommissioned when equipment essential for its operation has been removed. The IAEA uses an ‘essential equipment list’ to assist it in this determination. Designers are well suited to help the IAEA create such a list, which can be part of the design information provided to the IAEA at an early stage. During early design verification activities, the IAEA can check for the presence of items on the list in addition to their other activities. During the time from when the essential equipment arrives at the facility to when it is verified to have been removed from the site or verified to be inoperable, the facility is considered available for use. In order for the facility to be considered unable to be used, the IAEA must first verify the absence of essential equipment.

5

CONSIDERATIONS RELATED TO REACTOR VARIATIONS

This section discusses variations from a typical LEU fuelled LWR. In addition to the considerations covered in Section 4, designers/engineers can also consider how the reactor variations described below can affect IAEA safeguards implementation, and design concepts that can result from these impacts.

5.1 Modular Reactors

Designers of Small Modular Reactors (SMRs) for commercial use can consider aspects of these designs related to their safeguardability (the ease with which the facility can be safeguarded). Analysis of the safeguardability of a particular SMR design can take the detection resources into consideration that are needed to ensure that a conclusion can be drawn in a cost effective manner. SMRs can be expected to have the following characteristics that could affect the implementation of safeguards:

- *Low thermal signature*. Having a thermal footprint similar to other small-scale energy technologies currently deployed in remote locations implies that it will be challenging to use satellite or other forms of remote sensing to verify operation. However, indirect indicators such as 'lights on' or the operation of powered equipment in the absence of alternative power sources may be useful
- *Coolant*. Use of coolants other than water, such as lead-bismuth or sodium, does not allow for traditional optical viewing in the core nor of the spent fuel. The IAEA needs to be able to use operator-viewing systems for these routine inspection tasks. Authentication of these systems can be considered early on in the design process
- *Number of units per site*. One of the potential advantages of SMRs is that multiple individual reactor units can be added sequentially to one larger station, possibly sharing a single control room. However, from a safeguards standpoint, the larger the number of units, potentially the greater the number of refuelling and discharges per calendar year. It is possible that a common spent fuel pool might be used. These characteristics will need to be considered by the IAEA in determining its inspection approach and inspection frequency, including physical inventory verification, if an increase in inspection resources is to be avoided or minimized
- *Long-life reactor core, possibly fixed-bed core (sealed vessel)*. Reduced core access and reduced refuelling frequency makes misuse of operation and diversion of spent fuel (respectively) much more difficult. But this will need to be reconciled with the current IAEA practice of annual physical inventory of each reactor core, performed when access to the core is possible
- *Advanced fuel cycle*. In general, the nature of a non-LWR-based SMR operating off an advanced fuel cycle will almost certainly be unfamiliar to the safeguards inspection regime

and require significant analysis to understand the most efficient and effective safeguards approach. This presents an opportunity for safeguards experts to collaborate on the design

- *Enrichment*. If a design requires uranium fuel enriched above 20%, the IAEA significant quantity is decreased from 75 kg U-235 for LEU to 25 kg U-235 for HEU. As a result, increased safeguards measures may be required
- *Surplus reactivity*. A reactor designed for low refuelling frequency would likely have high surplus reactivity and burnable absorbers. Such a core would tolerate target irradiation without affecting key operational parameters that might be monitored and, from an observer's viewpoint, neutronic management with burnable absorbers would look similar to neutronic management with target material. Verifying that there is no possibility of access for target insertion or removal can be a design requirement. Potentially, these concerns can be mitigated with a pre-operation design verification activity by the IAEA coupled with reliable sealing and surveillance measures
- *Fuel element size*. Depending on design, core length can be significantly smaller than conventional designs, leading to shorter fuel elements and two opposing impacts on diversion difficulty: obtaining an SQ requires diverting more items and small size tends to render concealment easier. Reduced refuelling frequencies and sealed cores can mitigate some of the problems
- *Spent fuel storage geometry*. Smaller fuel elements would most likely need to be stored vertically for cooling purposes, with a strong economic incentive to stack fuel and reduce storage footprint. This geometry potentially challenges the current safeguards inspection activities due to lack of direct-line visibility of fuel elements from above

5.2 On-Load Reactors

On-load reactors require safeguards consideration of the increased frequency in spent fuel handling compared to most off-load reactors. Frequent movements of relatively-small, irradiated-direct-use items offers opportunity for non-destructive assay instrumentation to be installed within the primary containment to facilitate IAEA activities; but can require a designer to consider utilization of unattended systems that are remotely monitored or that require periodic servicing on-site by inspectors. Spent fuel verification within the spent fuel pool can challenge designers to consider methods for minimizing spent fuel movements, especially if the used fuel is stacked in layers. Since re-verification of the nuclear material inventory values can be disruptive and costly, additional measures such as redundancy or subdivision of sealed enclosures can be considered to resolve issues resulting from a potential loss of surveillance or to shorten the re-verification process.

Safeguards considerations include provision for:

- maintaining continuity of knowledge on the core with radiation-sensor-based core discharge monitors and bundle counters [17]
- facilitating IAEA verification and maintaining continuity of knowledge of irradiated fuel placed in layers for storage

- remote monitoring of IAEA equipment to verify its proper operation.

5.3 Pebble Bed and Prismatic Fuelled HTGRs

In addition to using nuclear reactors for generating electricity, research and development, and isotope production, it is important to note that a high-temperature gas-cooled reactor (HTGR) can be used for other commercial applications as well, such as very high temperature process heat (i.e. petrochemical and chemical processing, fertilizer production, crude oil refining). Designing safeguards relevant characteristics into the facility early will be important to maintaining flexibility in monitoring nuclear material inventory and flow when these reactors are deployed especially if they are integral to the associated industrial application.

5.3.1 Pebble Fuelled HTGRs

Safeguards considerations for the designer that are unique to a pebble fuelled HTGR:

- The seal and surveillance systems for the reactor core and irradiated pebble fuel storage vessels may be directed at the access hatches to those areas, rather than the vessels themselves, since they are in high radiation areas
- The IAEA will likely use fuel flow monitors to verify the fuel transfers to and from the associated pebble fuel storage vessels and reactor vessel(s). The fuel flow monitor will count, verify, and discriminate spent pebble fuel from fresh, irradiated, and damaged pebble fuel, and graphite pebble moderator
- IAEA seals may also be applied to the fresh pebble fuel storage drums and the pebble feed hopper(s) in the fresh fuel handling area. The designer can provide 0.5 m^2 for attaching, replacing, or servicing the seals
- The IAEA likely will use NDA techniques for verifying fresh (unirradiated) pebble fuel casks that are the same as those currently used for verifying fresh nuclear fuel containing LEU and MOX (i.e. gamma spectroscopy and passive and active coincident neutron counting). The selection and optimization of this equipment will be dictated by the pebble fuel size, geometry, and radionuclide content (i.e. U-235, U-233, plutonium and thorium). Two square meters of space is adequate for using most of these systems and they can all be powered using a local convenience electrical power outlet

5.3.2 Prismatic Fuelled HTGRs

Safeguards considerations for the designer that are unique to a prismatic fuelled HTGR:

- IAEA seals may be applied to the fuel pit covers in the fresh fuel storage area and in the gas-cooled spent fuel storage pits if dry storage is used. If spent HTGR fuel is stored in a pool, seals would normally not be used
- If the core or spent fuel cannot be presented easily for verification, then a radiation-based fuel flow monitoring system would likely be used to count and verify the irradiated HTGR fuel as it is transferred from the reactor core to the spent fuel storage area, and to detect undeclared reverse transfers of fuel. If the spent fuel storage area is difficult to access (e.g.

gas-cooled dry storage pits), the fuel flow monitor, possibly in combination with dual C/S measures, would be used to maintain the continuity of knowledge of spent fuel in storage. The fuel flow monitor will count, verify, and discriminate dummy fuel, fresh fuel, irradiated core fuel, and fully irradiated spent fuel. The designer can include the safeguards equipment and physical infrastructure in the design optimization

- Equipment that has been used for verifying fresh (un-irradiated) prismatic HTGR fuel is similar to the NDA equipment that the IAEA uses to verify LWR fuel containing LEU and MOX. The optimization and selection of this equipment will be dictated by the nuclear material content of the new prismatic HTGR fuel designs (i.e. whether they contain LEU, HEU, plutonium, thorium, and/or U-233).

5.4 MOX Fuelled LWRs

Fresh mixed plutonium and uranium fuel as MOX (mixed-oxide) fuel can be more safeguards sensitive than natural uranium or LEU fuel, particularly in reconstitutable[p] assemblies, as it contains direct use material. An adapted or optimized safeguards approach is usually required for MOX assemblies. Receipt, storage and movements within a reactor facility are more closely monitored in order to maintain continuity of knowledge over fresh MOX fuel. Once burned in an operating reactor the fuel contains substantial amounts of fission products and is considered irradiated direct use material, similar to irradiated UO_2 fuel — increasing its estimated conversion time to useable components of a nuclear explosive device. The following safeguards considerations can be taken into account:

- Measurement or surveillance of fresh MOX fuel under water can require more stringent[q] C/S measures and IAEA verification than fresh LEU fuel in storage does because of the plutonium content. Emerging technologies for measuring MOX fresh and spent fuel are currently under development
- Fresh MOX fuel storage time at the plant should be minimized and means provided for easily sealing the fresh MOX fuel within dry storage
- Consideration can be given to applying more stringent C/S measures to fresh MOX transfer pathways, including radiation detectors for nuclear material flow monitoring
- Spent fuel storage C/S of MOX fuel is consistent with the non-MOX spent fuel items for a reactor facility under IAEA safeguards. It may be desirable (i.e. less expensive) to cover both the dismantling station and the location of spent fuel storage in the spent fuel pool with single C/S using surveillance when wet storage is used

[p] Fuel assembly designs can include a requirement that they are easily disassembled for replacement of defective fuel pins at the reactor site.
[q] More stringent implies detection of both 1) within a shorter timeliness objective and 2) of a smaller quantity objective.

5.5 Research Reactors and Critical Assemblies

Numerous research reactor concepts have been developed and deployed around the world. Their design and flexibility are far more diversified than is the case for of power reactors. While the small scale of research reactors and critical assemblies (RRCAs) might suggest that a research reactor is not an important fuel cycle facility, they are a potential acquisition path that the IAEA monitors carefully.

The following design features or operational characteristics warrant safeguards consideration:

- RRCAs might be co-located with research facilities for the disassembly of irradiated items, such as hot cells
- RRCAs can be designed to facilitate irradiation of target samples
- RRCAs can be of small size and, therefore, easier to hide
- RRCAs are often operated intermittently
- RRCAs can be designed to use unirradiated HEU or plutonium in the fresh fuel or as targets
- Many RRCA fresh fuel items are easily carried by hand
- In older facilities, storage of significant amounts of irradiated fuel from RRCAs can be an attractive target for diversion

These characteristics offer additional possibilities (potential acquisition paths) for undeclared production of nuclear material or diversion of declared nuclear material compared to the baseline case. [23] [24] [25]

Specific safeguards issues to consider for RRCAs include:

- the possibility to store large quantities of fresh fuel including HEU, U-233 or plutonium, which are readily useable for weaponization at an RRCA facility
- the need to monitor fuel and target loading/unloading activities much more frequently, although these facilities involve much smaller quantities than found in larger reactors
- the possibility to irradiate targets of thorium (to produce U-233) or U-238 (to produce Pu-239), to produce direct use material
- the use of MOX fuel (covered in Section 5.4)
- the classification of HEU or plutonium fuel in critical assemblies that can remain considered as ‘un-irradiated’ even after use since the irradiation times can be so short that the radiation levels from the fuels drop quickly after use;
- even after extensive use, the enrichment of HEU fuel that was burned down from 93% and that may still exceed 20%, and thus be considered by the IAEA as ‘highly enriched’
- stores of loose items containing uranium or plutonium for research activities that may be present, which can complicate the material accountancy approach by not being amenable to item accountancy
- HEU that can be present for use as targets for the production of medical isotopes such as molybdenum-99 (Mo-99)

- separation of plutonium from fresh fuel that is easier than separating plutonium out of irradiated fuel
- fissile material production in an RRCA that can be optimized if the core is loaded with a 'driver' fuel to maintain criticality and surrounded by a 'blanket' fuel containing a target material. Consequently the IAEA can choose to pay close attention to potential diversion from stores of depleted, natural, and low-enriched uranium at an RRCA
- the potential for the IAEA to maintain safeguards coverage of 'decommissioned' RRCAs until they are verified to be inoperable to avoid misuse of the facility
- the possibility of remote monitoring being used in a cost-effective manner to reduce inspector activity on-site, yet maintain or improve safeguards effectiveness. One example of this approach is the use of the advanced thermo-hydraulic power monitoring system on research reactors that can independently assess coolant flow and heat extraction to calculate plutonium production in the core. This system is mounted on the primary core coolant loop in a non-penetrating manner
- fewer sensitive or proprietary issues for RRCAs compared to LWRs that allow more opportunity for safeguards data transmission off-site, live video feeds, monitoring of reactor power levels, or other characteristics of safeguards interest
- IAEA activities concerning hot cells
- checks of operating records for consistency to assess opportunities for undeclared irradiation or activities of safeguards interest in hot cells

5.6 Next Generation Technology

New Generation IV reactors offer opportunity to develop or adapt the in-line measurement or monitoring currently applied to some on-load reactors. Process monitoring or operational transparency [26] can make more complete use of the facility operator's process instrumentation as an additional safeguards measure. Concerns regarding independence of the results from the operator's control and data authentication are areas of current R&D. Consideration can be given to the fact that many non-destructive measurement techniques are dependent on the geometry of the fuel or container, and the heterogeneity or homogeneity of the nuclear material inside the container. Reducing the variation in the positioning of the item being measured can reduce measurement uncertainties. If fuel movements are performed without human access and access to fuel storage locations are similarly limited, remote monitoring of the fuel movements by suitably reliable, redundant systems can reduce the need for on-site inspections. Consideration can be given to improving the automated tools used to collect and review data from multiple sensors, including the necessary infrastructure that connects sensors to electronics, then to the computer systems and on to off-site inspector review stations. Designers can help to eliminate common-mode failure paths and to recommend suitable levels of redundancy and backup power to avoid loss of safeguards knowledge over the operating lifetime of the reactor.

Consideration of advanced statistical sampling techniques to monitor the (process) control of the reactor operations can require more notifications by the operator, including more detailed information (i.e. more detailed knowledge of nuclear material locations and movements than currently available), which can require consideration in the facility and operational design.

Another major difference of safeguards interest would be the potential co-location of a spent fuel processing facility with the reactor facility. The major nuclear security advantage of co-locating the reactor, reprocessing and fuel fabrication is the reduction of the transportation between sites of nuclear fuel compared to other nuclear energy systems. However, a bulk (re)processing facility would require more intrusive safeguards measures than the reactor-type item accounting facility and unless the two facilities can be easily proven to be separate and distinct, both would receive more intrusive application of safeguards. Similar concerns exist when pin replacement capability is on site. Clear segregation of any hot cells with pin handling equipment from the rest of the nuclear material handling and storage facilities will allow them to be placed under more stringent safeguards measures without affecting most of the facility's item accounting status.

5.7 Generation IV Liquid fuelled Reactors

For liquid fuelled reactors, designers can be aware that such reactors cannot be considered item facilities. Similar to pebble bed reactors, more stringent nuclear material accountancy measures can be required to verify the quantities, locations and movements of nuclear material. These measures can include, but are not limited to, fuel flow monitors, seals, video surveillance, the use of sensors to trigger other sensors, more accurate NDA measurements and sampling plans that select additional items for verification activities.

5.8 Fast Reactors

Reactors with a fast neutron spectrum are designed to use nuclear material more efficiently by recycling the plutonium found in irradiated fuel and by using more of the U-238 to breed plutonium. As such, fast reactors generally have larger amounts of plutonium present in the fresh and irradiated fuel than is found at LWR facilities. Additionally, some can use HEU fresh fuel. From a safeguards perspective, unirradiated plutonium and HEU receive greater attention than irradiated plutonium does. Therefore, fast reactor facilities are likely to receive more frequent inspections involving more measurements or more C/S measures. However, the plutonium produced in fast reactors has less variation in the Pu-239 fraction, which facilitates NDA measurements.

Some fast reactor designs under consideration are intended to use reactor core fuel containing layers or zones of fertile material or/and minor actinides, or other constituents like burnable poisons that could require development of new measurement methods and new calibration material. Because most fast reactors are in the earlier stages of development and design maturity, designers have a greater opportunity for inclusion of safeguards in the design considerations. These considerations include:

- early provision of design information before it is finalized

- provision of additional information by the State regarding nuclear facilities and activities related to the fuel cycle
- hardened, secure storage for plutonium, HEU or transuranic fuel
- advanced, redundant containment and surveillance systems
- continuous, unattended NDA to monitor fuel movements that can distinguish between fissile and fertile or non-nuclear material item
- the implications of minor-actinide bearing fuels on the implementation of safeguards [27]
- clear segregation of any hot cells and pin handling equipment from the rest of the reactor facility to allow them to be placed under more stringent safeguards measures without affecting the majority of the facility's item accounting status

6
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A

ABBREVIATIONS AND ACRONYMS

AP	Additional Protocol
CDM	Core Discharge Monitor
CoK	Continuity of Knowledge
CSA	Comprehensive Safeguards Agreement
C/S	Containment & Surveillance
Cs-137	Cesium isotope with atomic mass of 137
DIQ	Design Information Questionnaire
DIV	Design Information Verification
DOE	Department of Energy
FA	Facility Attachment
GIF	Generation IV International Forum
HEU	Highly-Enriched Uranium
HTGR	High-Temperature Gas-cooled Reactor
IAEA	International Atomic Energy Agency
IKMP	Inventory Key Measurement Point
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
KMB	Key Measurement Point
LEU	Low-Enriched Uranium
LWR	Light Water Reactor
MBA	Material Balance Area
MOX	Mixed Oxide fuel (i.e. ceramic of plutonium and uranium oxides mixture)
NDA	Non-Destructive Assay
NGSI	Next Generation Safeguards Initiative

NMA	Nuclear Material Accountancy
NNSA	National Nuclear Security Administration
NNWS	Non-Nuclear Weapon State
NPP	Nuclear Power Plant
NPT	Non-Proliferation Treaty (*Treaty on the Non-Proliferation of Nuclear Weapons*)
NWS	Nuclear Weapon State
RRCA	Research Reactors & Critical Assemblies
RSRA	Regional Safeguards Regulatory Authority
SBD	Safeguards-by-Design
SMR	Small Modular Reactor
SQ	Significant Quantity
SRA	State Regulatory Authority
U-233	Uranium isotope with atomic mass of 233
U-235	Uranium isotope with atomic mass of 235

B

IDENTIFYING SAFEGUARDABILITY ISSUES

This appendix describes a facility safeguardability analysis approach[r]. It can be used as a structured approach to understand and identify potential safeguards issues. The design team can include an international safeguards expert to help the team prepare for interaction with the safeguards authority and/or the IAEA.

If the operator is building or modifying a standardized facility design for which a well-understood safeguards approach exists, the effort to analyse its safeguardability may be very modest. However, it may be possible to make existing safeguards tools and measures more efficient with slight modifications to the design or operating procedures.

A greater effort to assess facility safeguardability can be useful for facilities that include novel design features or that present particular safeguards challenges. Innovative designs different from those for which IAEA safeguards approaches are known can present safeguards problems that could be addressed by the designer, who could help mitigate them or accommodate innovative safeguards tools and measures.

Potential safeguards issues can arise in the following ways. Design differences can:

- create additional or alter existing diversion paths
- increase the difficulty of design information examination and verification
- impede the IAEA's capability to verify that diversion has not taken place
- create a new or alter an existing potential for the facility to be misused

[r] BARI, R.A., et al., Facility Safeguardability Assessment Report, Pacific Northwest National Laboratory Report, PNNL-20829 (October 2011)

Table B-1
Facility Safeguardability Assessment

Facility Safeguardability Assessment Screening Questions	
1. Does this design differ from the comparison design / process in ways that have the potential to create additional diversion paths or alter existing diversion paths?	Yes / No
1.1. Does this design introduce nuclear material of a type, category, or form that may have a different significant quantity or detection time objective than previous designs/processes (e.g., mixed oxide rather than low enriched uranium, irradiated vs. unirradiated or bulk rather than items)?	Yes / No
1.2. Does this design layout eliminate or modify physical barriers that would prevent the removal of nuclear material from process or material balance areas, e.g., circumventing a key measurement point (KMP)?	Yes / No
1.3. Does this design obscure process areas or material balance area (MBA) boundaries making containment/surveillance or installation of verification measurement and monitoring equipment more difficult?	Yes / No
1.4. Does this design introduce materials that could be effectively substituted for safeguarded nuclear material to conceal diversion?	Yes / No
2. Does this design differ from the comparison design in a way that increases the difficulty of design information examination (DIE) and verification (DIV) by IAEA inspectors?	Yes / No
2.1. Does the design incorporate new or modified technology? If so, does the IAEA have experience with the new or modified technology?	Yes / No
2.2. Are there new design features with commercial or security sensitivities that would inhibit or preclude IAEA inspector access to equipment or information?	Yes / No
2.3. Do aspects of the design limit or preclude inspector access to, or the continuous availability of, Essential Equipment for verification or testing?	Yes / No
2.4. Are there aspects of the design that would preclude or limit IAEA maintenance of Continuity of Knowledge (CoK) associated with design verification during the life of the facility.	Yes / No
3. Does this design/process differ from the comparison design / process in a way that makes it more difficult to verify that diversion has not taken place?	Yes / No
3.1. Does this design lessen the efficiency of physical inventory taking (PIT) by the operator or the effectiveness of physical inventory verification (PIV) by the IAEA?	Yes / No
3.2. Does this design impair the ability of the operator to produce timely and accurate interim inventory declarations or for the IAEA to perform timely and accurate Interim Inventory Verification (IIV)?	Yes / No
3.3. Does this design impede timely and accurate inventory change (IC) measurements and declarations by the operator and verification by the IAEA?	Yes / No
3.4. Does this design impede the introduction of or reduce the usefulness of Other Strategic Points (OSP) within a Material Balance Area (MBA)?	Yes / No
4. Does this design differ from the comparison design in ways that create new or alter existing opportunities for facility misuse or make detection of misuse more difficult?	Yes / No
4.1. Does this design differ from the comparison facility / process by including new equipment or process steps that could change the nuclear material being processed to a type, category, or form with a lower significant quantity or detection time objectives?	Yes / No
4.2. Should the comparison facility safeguards approach employ agreed upon short-notice visits or inspections, measurements, or process parameter confirmations, would this design preclude the use of or reduce the effectiveness of these measures?	Yes / No
4.3. Do the design and operating procedures reduce the transparency of plant operations (e.g., availability of operating records and reports or source data for inspector examination or limited inspector access to plant areas and equipment)?	Yes / No

Table B-2
Effect of Design Differences on Physical Inventory Verification

3.1. Does this design lessen the efficiency of physical inventory taking (PIT) by the operator or the effectiveness of physical inventory verification (PIV) by the IAEA?	Yes / No
3.1.1. Does the plant/process design reduce the measurement accuracy or otherwise impede the use of Inventory Key Measurement Points (IKMP). If so, are there other well defined locations that could be considered by the IAEA as IKMPs.	Yes / No
3.1.2. Does the plant/process design impede or preclude the collection/storage of inventory at IKMPs at the time of PIT/PIV?	Yes / No
3.1.3. Does the design preclude PIT/PIV measurements on some inventory? If so, does the new design include features to permit CoK to be maintained from a previous measurement and verification?	Yes / No
3.1.4. Does the design/process employ nuclear material types, categories, or forms that are more difficult to measure accurately at IKMP? If so, can the plant accountancy measurement systems meet International Target Values (ITV) for the PIT?	Yes / No
3.1.5. Does the design preclude or limit the ability of the IAEA to take/analyze independent samples for the PIV?	Yes / No
3.1.6. Does the process design preclude controls to prevent inventory change or movement between the time of the PIT and the PIV? If so, does the design include measures to maintain CoK of the changed or moved inventory between the time of the PIT and the PIV?	Yes / No

Table B-3
Effect of Design Differences on Interim Inventory Verifications

3.2. Does this design impair the ability of the operator to produce timely and accurate interim inventory declarations and for the IAEA to perform timely and accurate Interim Inventory Verification (IIV) for timeliness?	Yes / No
3.2.1. Does design impede or preclude shutdown of the process for an IIV?	Yes / No
3.2.2. Does the design impede or preclude the collection/storage of inventories at IKMP, which provide access for measurement and declaration by the operator and verification by the IAEA, at the interim inventory cut-off time (CoT)?	Yes / No
3.2.3. Does design create the potential for Un-Measureable Inventory (UMI) at the time of an IIV in locations such as pipes, pumps, or evaporators? If so, can the UMI be accurately estimated by the operator and can the estimation method be verified by the IAEA?	Yes / No
3.2.4. Does the new plant / process design increase the time required for the operator to provide the IAEA with an Interim Inventory List (IIL) after the CoT	Yes / No
3.2.5. Does design increase the expected overall measurement uncertainty of the operator's interim inventory declaration?	Yes / No
3.2.6. If the comparison facility Safeguards Approach included short-notice or no-notice interim inspections, does the design include real time measurement and accounting systems that allow for almost immediate inventory declarations required to support such inspections?	Yes / No

Table B-4
Effect of Design Differences on Inventory Change Measurement

3.3. Does this design impede timely and accurate inventory change (IC) measurements and declarations by the operator and verification by the IAEA?	Yes / No
3.3.1. Does this design reduce the accuracy of or otherwise impede the use of customary Flow Key Measurement Points (FKMP). If so, are there other well defined locations that can be considered by the IAEA as FKMP?	Yes / No
3.3.2. Does the design increase the measurement uncertainties at FKMPs? If so, can the plant accountancy system meet International Target Values (ITV) for inventory changes**?**	Yes / No
3.3.3. Does the new design impede or preclude IAEA verification of the IC declarations by sample taking, portable or installed measurements systems, or by joint-use of authenticated operator systems?	Yes / No
3.3.4. Does the design impede or preclude IAEA verification of calculated IC declarations such as nuclear material loss and gain?	Yes / No
3.3.5. Does the design impede or preclude IAEA verification of IC declarations that are determined indirectly or based on historical measurement data (e.g. waste transfers to retained waste or measured discards), decrease the accuracy of the determinations, or limit the availability of the historical data.	Yes / No
3.3.6. Does the design increase the time required for the operator to measure, calculate, prepare, and approve the IC declarations?	Yes / No
3.3.7. Does the new design increase the expected overall measurement uncertainty of the operator's inventory change declaration?	Yes / No

Table B-5
Effect of Design Differences on Other Strategic Points

3.4. Does this design impede the introduction of or reduce the usefulness of Other Strategic Points (OSP) within a Material Balance Area (MBA)?	Yes / No
3.4.1. Would OSP be less effective in providing CoK of measured/verified nuclear material (e.g., reduce the effectiveness of surveillance systems or containment devices; make installation of these systems / devices more difficult; impede or preclude access to or maintenance of these systems / devices; make interfaces [e.g., utility support or data transmission] more difficult)?	Yes / No
3.4.2. Would OSP be less effective in providing additional assurance for high uncertainty verifications done at KMPs (e.g., reduce opportunities for random short-notice sampling by IAEA inspectors; reduce or eliminate opportunities for correlation with measurement data at related locations, reduce the scope or accuracy of Process Monitoring; or limit or preclude IAEA ability to authenticate plant PM systems or introduce independent systems)?	Yes / No