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Implementing Safeguards-by-Design

Trond Bjornard
Robert Bean
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Idaho National Laboratory

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Trond Bjornard
Robert Bean
Phillip Casey Durst
John Hockert[1]
James Morgan[2]

[1]PNNL
[2]ORNL

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Idaho National Laboratory
Nuclear Nonproliferation Division
Idaho Falls, Idaho 83415

http://www.inl.gov

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EXECUTIVE SUMMARY

Safeguards-by-Design (SBD) is a new approach to the design and construction of nuclear facilities in which nuclear safeguards provisions and features are designed into the facility from the very beginning of the design process. It is a systematic and structured approach for fully integrating international and national safeguards (MC&A), physical protection, and other barriers into the design and construction process for nuclear facilities, while integrating with safety and other project considerations. Because the successful implementation of SBD is primarily a project management and coordination challenge, this report focuses on that aspect.

To improve the implementation of nuclear safeguards worldwide, the United States National Nuclear Security Administration's (NNSA's) Office of International Regimes and Agreements (NA-243) commissioned a U.S. DOE National Laboratory project team to study how SBD could be implemented. This is in support of the NNSA Next Generation Safeguards Initiative (NGSI). The long term objective is to promote the global implementation of SBD so that new nuclear facilities will be designed with nuclear safeguards, safety, and physical protection features incorporated into the facility. This will make new nuclear facilities safer, more secure, and more easily safeguarded. In addressing these issues early in the design stage, it will also be more cost effective, by avoiding the costly retrofits to accommodate these requirements after the facility starts up.

In 2008, the SBD project team developed a high-level framework for institutionalizing SBD. As a result, the establishment of SBD as a global standard was found to depend on three pillars: 1) **Requirements Definition**, including the definition of requirements and criteria for successful safeguards performance, 2) **Design Processes**, including project management and coordination, and 3) **Design Toolkit**, including the technology and methodology used in the design and assessment of performance against requirements. These in turn were seen as resting on the foundation of **Institutionalization**, including education, outreach, training, and standardization. Each of these areas is vital to successfully establish SBD as a global standard.

The present report continues the work begun in 2008 and focuses on the design and construction process - specifically, project management and coordination. This includes project planning, definition, organization, coordination, scheduling, communication and interaction between the domestic and international safeguards authorities, facility builders, owner/operators, and other stakeholders during the design and construction of a nuclear facility. It further specifies the stages in an ideal nuclear facility design and construction project and identifies: 1) **When safeguards design activities take place, 2) When safeguards stakeholders should be involved, 3) The interaction between safeguards requirements, analysis, and decision making relevant to plant design, and 4) The documents for recording this process, analysis, and decision making.** In defining this process, the SBD project team has followed the successful and analogous example of the Safety-by-Design process and methodology developed by the U.S. DOE for nuclear projects within the United States.

The principal conclusions from this study are as follows:

- **The successful implementation of SBD is principally a project management challenge.** Immediate benefits can be obtained through the incorporation of the key elements of SBD and timely and well-coordinated interaction of stakeholders, using an agreed project timeline.

- **Input from the nuclear industry indicates that the safeguards requirements, facility attachment, and safeguards approach should be defined early in the design process - perhaps as early as the preliminary design stage**. However, for large and complex nuclear facilities the facility attachment and safeguards approach often continue to evolve before they are finalized prior to start-up of the facility. This indicates that the facility operator, national

regulator, and IAEA need to communicate at an earlier stage in the design process to define and resolve issues relevant to the design and incorporation of safeguards relevant features.

- **Life-cycle cost (LCC) analysis can be a useful tool in safeguards design for examining the cost trade-offs** associated with the capital costs of intrinsic design features for safeguardability, versus the later operational costs (including IAEA verification activities). This will only work, however, if the facility owner/operator addresses IAEA costs when they perform the LCC analysis. At present there is no motivation to do so. This warrants further examination.

- **The use of a Safeguards Effectiveness Report (SGER) is proposed to document safeguards requirements, criteria, specifications, and performance evaluations for safeguards systems during the design and construction of nuclear facilities**. It is intended to be a living document that would contain increasing detail about safeguards measures and activities as the design matures. The primary benefit of the SGER is that it would gather all of the safeguards relevant information for the design and construction of a nuclear facility in one convenient place, subject to the overview of the facility operator/owner, national regulator, and IAEA. It would also more effectively track the evolution of the safeguards approach and measures, including physical protection, and document clearly how the designer plans to meet these requirements.

- **The content of the SGER could be used to complete the IAEA design information questionnaire (DIQ) and draft facility attachment (FA) for the respective facility.** This document would also serve to further integrate safeguards, safety, and physical protection during the design process.

- **The SGER would include a section regarding the evaluation of various safeguards measures and approaches to meet these criteria**. In this regard, there is a current need for an evaluation methodology for comparing and evaluating safeguards measures and approach options, relative to defined requirements. The Proliferation Resistance and Physical Protection (PRPP) analysis methodology has the potential to be used by the facility designer to compare, evaluate, and optimize safeguards measures and approach options. However, further development and demonstration of the PRPP methodology in this role is necessary.

- **The SGER should identify the minimum installation requirements and specifications for safeguards related equipment and systems**. As a minimum, these should include: i) space requirements, ii) utility requirements, including electrical mains and emergency backup power, iii) data transmission requirements, including special communication protocols or tamper resistance, and iv) cable and pass-through port penetrations. Knowing this information at an early stage (i.e., no later than the end of the preliminary design stage), would minimize costly facility retrofits to accommodate safeguards systems during or after facility startup.

Further work is required in a number of areas. The authors note that other studies supported by the Next Generation Safeguards Initiative (NGSI) are addressing the development of requirements and performance criteria, as well as contributing to the design toolkit through the development of technology, methodology, and safeguards guidelines for designers.

To further develop and demonstrate SBD, the SBD project team recommends the following to NNSA:

- **In the short term, conduct a domestic workshop with representatives from the nuclear industry** to ensure that their perspectives and needs are factored into further development of the SBD process. [High priority and vital to successful implementation]

- **In the short term, provide relevant SBD project reports to the IAEA, and support them in hosting a second international SBD (3S) technical workshop** to be attended by representatives from IAEA Member States, industry, national regulatory authorities, and other stakeholders (e.g. facility designer/builders, owner/operators, etc.). [High priority and vital to successful implementation]

- **In the medium term, continue to support the demonstration of the SBD process in the design and construction of the DOE Next Generation Nuclear Plant (NGNP)** until the completion of the preliminary design. The NGNP is a U.S. DOE led project with industrial partners, to design and license a high-temperature gas-cooled reactor (HTGR). Conceptual design of the NGNP is expected to begin in the spring of 2010. [Moderate priority]

- **In the longer term, consider the use of SBD in other DOE projects**. [High priority if SBD is to be implemented within DOE]

ACKNOWLEDGEMENTS

Funding for this study and the preparation of the final report was provided by the NNSA Office of International Regimes and Agreements (NA-243) under the SBD Project, and in support of the Next Generation Safeguards Initiative. The authors wish to thank the Office of NA-243 for their support, input, and direction in preparing this report. The authors also wish to thank Mr. Mark Schanfein and Quinn Grover of INL for reviewing and editing the final report.

CONTENTS

FIGURES

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LIST OF ACRONYMS AND ABBREVIATIONS

3S	(IAEA) Nuclear Safety, Security, and Safeguards
3SBD	(IAEA) Nuclear Safety, Security, and Safeguards by Design
10 CFR 830	United States Code of Federal Regulations 10, Part 830, “Nuclear Safety Management”
AFCI	(U.S. DOE) Advanced Fuel Cycle Initiative
AP	(IAEA) Additional Protocol (See also INFCIRC/540)
BWXT	Babcock and Wilcox Technologies Company
CA	Complementary Access (under the Additional Protocol)
CCB	Configuration Control Board
CD	Critical Decision
CDR	Conceptual Design Report
C/S	(IAEA) Nuclear Safeguards Containment/Surveillance Systems
CSA	(IAEA) Comprehensive Safeguards Agreement (See also INFCIRC/153)
CSDR	Conceptual Safety Design Report
DIE	(IAEA) Design Information Examination
DIQ	(IAEA) Design Information Questionnaire
DIV	(IAEA) Design Information Verification
DIVP	(IAEA) Design Information Verification Plan
DOE	United States Department of Energy
EFL	(NWS) Eligible Facilities List
FA	Facility Attachment (also called a Subsidiary Arrangement to the Safeguards Agreement)
GEN-IV	Generation IV International Forum (a.k.a. GIF, i.e., next generation nuclear energy system)
“Global”	Bi-Annual Conference on the Nuclear Fuel Cycle and Associated Issues
I&C	Instrumentation and Control (design or diagram)
IAEA	International Atomic Energy Agency
ICR	(IAEA) Nuclear Material Inventory Change Report
INCOSE	International Council on Systems Engineering
INFCIRC/66	(IAEA) Older Safeguards Agreement (now only with India, Israel, and Pakistan)
INFCIRC/153	(IAEA) Comprehensive Safeguards Agreement
INFCIRC/540	(IAEA) Protocol Additional to the Safeguards Agreement
INL	(U.S. DOE) Idaho National Laboratory
INPRO	(IAEA) International Project on Innovative Nuclear Reactors and Fuel Cycles
ISO	International Standards Organization

JNFL	Japan Nuclear Fuel Limited
LANL	(U.S. DOE) Los Alamos National Laboratory
LCC	Life-Cycle Cost
MBR	(IAEA) Nuclear Material Balance Report
MC&A	Nuclear Material Control and Accounting
MPC&A	Nuclear Material Protection, Control, and Accounting
NA-243	(NNSA) Office of International Regimes and Agreements
NGSI	(NNSA) Next Generation Safeguards Initiative
NNSA	(U.S. DOE) National Nuclear Security Administration
NNWS	(NPT) Non-Nuclear-Weapons State
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NRC	United States Nuclear Regulatory Commission
NWS	(NPT) Nuclear-Weapons State
Order 413.3A	DOE Order 413.3A on "Program and Project Management for the Acquisition of Capital Assets"
ORNL	(U.S. DOE) Oak Ridge National Laboratory
P&ID	Piping and Instrumentation Drawing
PFD	Process Flow Diagram
PIL	(IAEA) Nuclear Material Physical Inventory Listing
PMP	Project Management Plan
PNNL	(U.S. DOE) Pacific Northwest National Laboratory
PRPP	Proliferation Resistance and Physical Protection Assessment Methodology
PRRA	Proliferation Risk Reduction Assessment
SBD	Safeguards-by-Design
SDIT	(U.S. DOE) Safety Design Integration Team
SE	Systems Engineering
SGER	(Proposed) Safeguards Effectiveness Report
SLA	(IAEA) State-Level Safeguards Approach
SME	(DOE/NNSA) Subject Matter Expert
SRD	System Requirements Document
SSAC	(IAEA) State System of Accounting for and Control of Nuclear Material
STD-1189	(U.S. DOE) Standard-1189, "Integration of Safety into the Design Process"
STR	(IAEA) Scientific and Technical Report

NOTES ON NOMENCLATURE

In the field of nuclear safeguards and security, similar terms are sometimes used with different meanings by national and international organizations and institutions. To avoid confusion, the definitions of key terms used in this report are as follows:

- *Material Control and Accountability* (MC&A) means those measures applied (or required) by a state to nuclear facilities and activities to detect or deter theft or diversion of nuclear materials and provide assurance that all nuclear materials are accounted for. MC&A includes the statistical sampling of nuclear material, verification of plutonium, uranium, Pu-239, and U-235 content by destructive and non-destructive assay (DA & NDA), and accounting techniques for verifying the inventory and changes in inventory of uranium and plutonium bearing materials. MC&A measures employed by the state are comparable, but not identical, to the nuclear material accountancy measures employed by the IAEA to implement international nuclear safeguards.
- *Physical protection* means those measures applied (or required) by a state to nuclear facilities and activities to prevent unauthorized removal or sabotage of special nuclear material in use, storage, and transport. Special nuclear material includes enriched uranium and plutonium bearing materials.
- *Safeguards, or international safeguards,* means those measures applied by the International Atomic Energy Agency (IAEA) within a state to verify that nuclear material in all of the state's peaceful nuclear activities is not diverted to nuclear weapons or other nuclear explosive devices. Measures applied by the IAEA include nuclear material accountancy, as well as additional measures including information analysis, nuclear material containment and surveillance (C/S), and facility design information examination and verification (DIE/DIV), among others.
- *State System of Accounting for and Control of nuclear material* (SSAC) means those organizational arrangements at the national level which may have both a national objective to account for and control nuclear material in the state, and an international objective to provide the basis for the application of IAEA safeguards under an agreement between the state and the IAEA. The SSAC is typically the state's official point of contact with the IAEA for the transmission of safeguards relevant reports and information from the state, and communication channel to the facility operator regarding the application of international safeguards.

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Implementing Safeguards-by-Design

1. INTRODUCTION

Safeguards-by-Design (SBD) is a new approach to the design and construction of nuclear facilities in which nuclear safeguards provisions and features are designed into the facility from the very beginning of the design process. It is a systematic and structured approach for fully integrating international and national safeguards (MC&A), physical protection, and other barriers into the design and construction process for nuclear facilities, while integrating with safety and other project considerations. Because the successful implementation of SBD is primarily a project management and coordination challenge, this report focuses on that aspect.

Section 1 of this report describes the background and evolution of the SBD process, defines the key elements, and identifies the responsible parties in this process, i.e. stakeholders, and their roles. Section 2 describes the ideal stages in the design and construction process for a nuclear facility. The example of the ideal case also identifies the specific roles of the nuclear facility operator, designer/builder, national regulator, State System of Accounting for and Control of nuclear material (SSAC), and the IAEA at the various stages in this process. ***Whenever new activities or deliverables under the SBD process are identified, or are proposed at an earlier stage than the current process, they are identified in bolded italics for added emphasis.*** Section 3 describes the potential role of life-cycle cost (LCC) analysis in SBD. Section 4 introduces and proposes the use of a Safeguards Effectiveness Report (SGER) during the process, which could be used to document and define the relevant safeguards requirements and criteria, specify how these criteria will be met, and compare and evaluate prospective safeguards measures or options. Section 5 discusses the related international effort to implement SBD, also called Safety, Security, and Safeguards (3S), as currently coordinated by the International Atomic Energy Agency (IAEA).

Designing and constructing a nuclear facility is an extremely complex undertaking. The authors have made efforts to use terminology and project management concepts that are generally universal, so that the concepts might be more easily understood and used on a national and international level. The stakeholders in an actual project are many – facility owner, operator, designer, builder, national regulator, primary contractor, vendor, subcontractors, project management team, safeguards experts, safety experts, security experts, the IAEA, etc. The purpose of the present report is consider how SBD could be implemented, and to present the SBD approach to the broader international safeguards community. It is hoped that this will serve as a basis for future discussions amongst stakeholders to develop an internationally accepted SBD process that will be as simple as possible, yet practical and beneficial for all stakeholders, and one which can be used globally to improve the safety, security, and safeguarding of new nuclear facilities.

1.1 Background and Elements of Safeguards-by-Design

The NNSA Office of International Regimes and Agreements (NA-243) commissioned a U.S. DOE National Laboratory team to study how SBD could be implemented, in support of the Next Generation Safeguards Initiative (NGSI) to improve the implementation of nuclear safeguards worldwide. The initial effort also received support from the U.S. DOE Advanced Fuel Cycle Initiative (AFCI) Safeguards Campaign, because it is also relevant to the design and construction of American nuclear facilities. In February 2009, the NNSA SBD project team published the report "Institutionalizing Safeguards-by-Design: A High Level Framework."[1] The report describes a broad framework to develop and institutionalize the SBD concept. The framework divides the development into four major areas: **1) requirements definition, 2) design processes,** including project management and coordination**, 3) technology/methodology,** i.e., the designer's know-how and toolkit**, and 4) institutionalization.** The long-term objective is to promote the global application of the SBD process as an international standard to make new nuclear facilities safer, more secure, and easier to safeguard.

During the past two years, the idea of incorporating elements to improve nuclear safeguards earlier in the design process has garnered increased recognition and support from a number of international organizations, government agencies, national regulators, and the commercial nuclear industry. In October 2008, the International Atomic Energy Agency (IAEA) hosted an international workshop in Vienna, Austria, to discuss how nuclear safeguards could be more easily facilitated in nuclear plant design and operation. Attendees from the IAEA, IAEA Member States, national government agencies, and the commercial nuclear industry studied this issue and produced a workshop report recommending the further development of a process analogous to SBD and a proposed path forward.[2] In November 2008, the U.S. Nuclear Regulatory Commission (NRC) issued the "Policy Statement on the Regulation of Advanced Reactors." In this policy statement, it states NRC expectations that reactor designers consider the threat of nuclear material theft, and specifies requirements for implementing international safeguards monitoring early in the design phase. It further notes that design features, *"…could assist in establishing the acceptability or licensability of a proposed advanced reactor design, and therefore should be considered in advanced designs."*[3] At the Global 2009 conference held in Paris, France, Areva/Canberra presented a paper that supports the SBD concept, which they referred to as '3SBD' - for safety, safeguards, and security by design. They suggest that synergistic benefits could be gained in the future with full implementation of a mature SBD process.[4] During the summer of 2009, the four commercial nuclear suppliers working within the DOE AFCI (Areva, BWXT, JNFL, and Energy Solutions) reviewed and commented on the SBD High Level Framework Interim Report. Those comments, together with an assessment of their implication for the path forward, were published in the report *Safeguards by Design: High Level Framework - An Evaluation of Industry Response*.[5] The general consensus from all of these is a strong endorsement of the SBD (or '3SBD') concept, subject to a number of concerns. Of primary concern to industry is that the SBD process must be voluntary and benefit all of the key stakeholders. This clearly defines a principal challenge for further development of SBD. While the application of the SBD process may be seen as discretionary, the application of domestic and international nuclear safeguards is binding and subject to national regulation by domestic authorities and international verification by the IAEA. The ultimate vision of SBD is to better understand the relevant safeguards requirements, criteria, and options earlier in the design process so that nuclear facilities can be more effectively and more efficiently safeguarded. The goal of the vision is clear. However, the path to the goal is what presents the challenge.

The present report continues the work begun in 2008 in support of the NNSA Next Generation Safeguards Initiative, under the NA-243 sponsored SBD Project. A number of studies that complement the present report are being prepared in parallel under the NNSA SBD Project. They focus on defining the safeguards requirements and developing enabling technology and methodology, while the present report focuses on the design process. One study examines the issue of requirements and success criteria needed to implement international safeguards at particular nuclear facilities. Additional studies address the technical know-how required to implement SBD (i.e. design toolkit), including safeguards relevant lessons learned from prior projects and safeguards guidelines for designers.[6, 7]

Figure 1 depicts a graphical view for establishing SBD as a global standard, as presented in the *Institutionalizing Safeguards by Design: High Level Framework,* hereafter referred to as the *High Level Framework Report*. The objective of universal application of SBD is supported by three pillars and a foundation, all of which are vital to success. The first pillar is **Requirements Definition,** which includes definition of the criteria by which one measures whether the requirements have been met. Modern design and construction projects for nuclear facilities are generally requirements driven, and many of the stakeholders in the project impose requirements on the facility design or construction process. Generally speaking, the regulators and oversight agencies, including the IAEA, specify requirements for the safeguards, MC&A, and physical protection systems, which may be either prescriptive or performance oriented. At the aforementioned IAEA hosted workshop, industry representatives stated their preference that requirements for international safeguards be defined to give the facility designers flexibility to propose approaches that best meet overall needs.[2] While this is important input, one must recognize that IAEA safeguards criteria and inspection requirements remain largely prescriptive. Consequently, further discussion between the IAEA Inspectorate, IAEA Member States, and the nuclear industry will be required to determine if performance based rather than prescriptive criteria can be developed.

The idea that the designer may develop and propose a safeguards approach suited to a particular facility is implied in the state's safeguards agreement with the IAEA, based on INFCIRC/153 (corrected).[8] As shown in the paragraph-4 quoted below, the safeguards agreement stresses that nuclear safeguards be efficiently implemented and in a non-intrusive manner:

"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."

Consequently, it can be argued that the facility designer can propose how safeguards are to be efficiently and non-intrusively implemented in the new facility.

Workshop participants, including representatives from the IAEA, agreed that work is needed to define safeguards requirements and criteria in greater detail in order to meet designers' needs for clearer input.

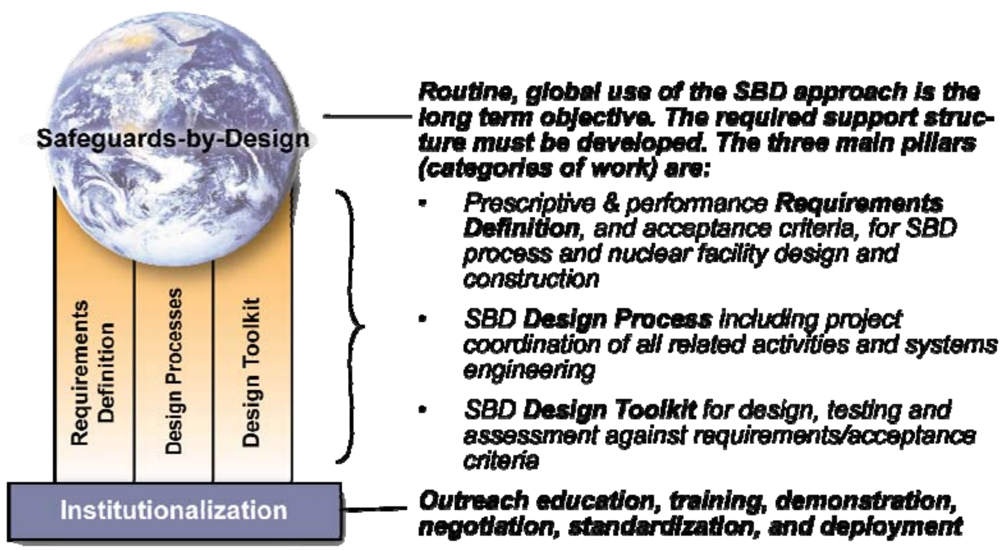

Figure 1. Required support structure for implementing SBD.

The central pillar of Figure 1 is **Design Processes**. As noted in the DOE study, *Review and Analysis of Development of Safety by Design Requirements*,[9] the primary audience for requirements and guidance documents are the project managers who will implement SBD. There are a number of examples of nuclear projects in and outside the United States, where safeguards and security features were incorporated late in the design process, causing project cost overruns, schedule delays, and costly facility retrofits. Such problems can be avoided when the safeguards and security teams are intimately involved in the project from the very beginning and effective project coordination, project management, and systems engineering are used to identify, coordinate, and schedule the activities of all stakeholders. The IAEA workshop participants agreed on the high importance of project scheduling and coordination, noting it was essential that a timeline of all related activities be developed and mutually agreed by all parties. It is important to note that such a mini-project plan for the development and application of international safeguards would normally fall outside the current project management approach. Additionally, this plan would require the mutual agreement of the facility project team, the national regulator and SSAC (if different from the national regulator), as well as IAEA. This central pillar is the focus of this report and will be discussed in more detail.

The third pillar in the framework is **Design Toolkit**, which can be thought of as containing the technical know-how, technologies and methodologies, needed to design, evaluate, and implement the safeguards systems. Included in this category are relevant standards, designer guidelines, recommended best practices, models used for design of safeguards systems, and safeguards performance evaluation methods.[10,11] Under the SBD approach, the latter may be used to assess performance of the safeguards systems and demonstrate compliance with the defined requirements.

The foundation for global implementation of SBD is **Institutionalization**, which consists of all of the activities required to develop and gain widespread adoption of the SBD approach, including: industry outreach, collaboration, education, training, demonstration, standardization, regulation and deployment. Development of some of the pillars will require participation by several stakeholders in order to ensure that the SBD approach reflects their needs. The discussions and collaborations required to achieve broad consensus on the implementation approach is another example of an institutionalization activity.

1.2 Key Aspects of the Safeguards-by-Design Process

The focus of the present report is the central pillar, Design Processes, including project management and coordination. The key elements of SBD are illustrated in Figure 2. As shown graphically, each element is an integral part of the whole SBD Process.[12] There are multiple requirements and inputs. Ultimately, all must be addressed in a complementary manner in order to implement SBD.

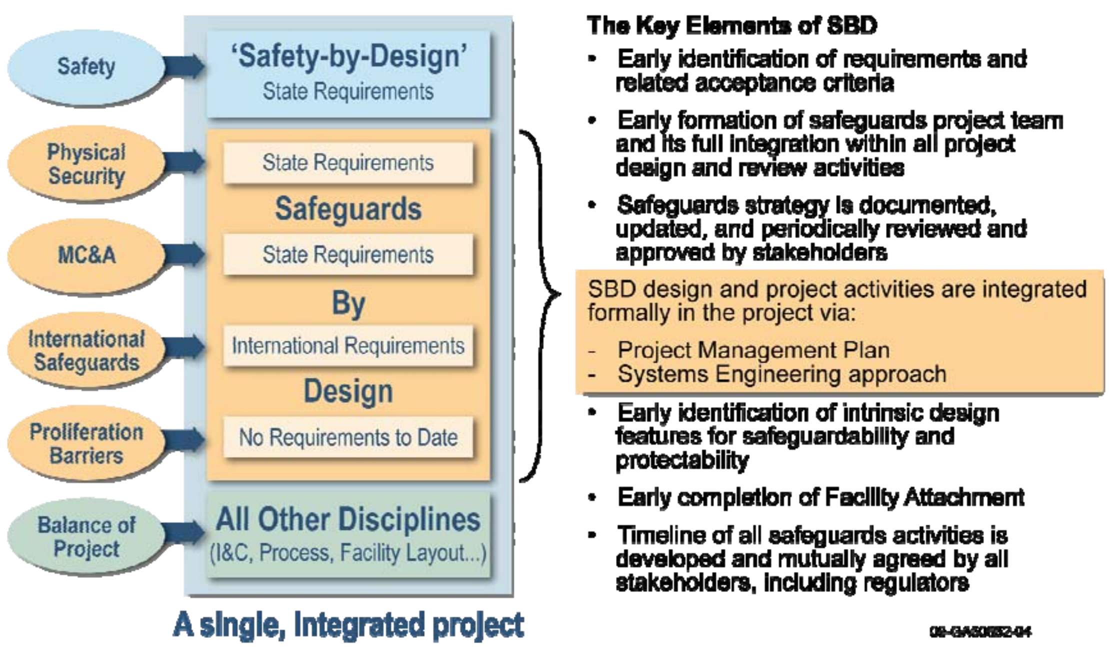

Figure 2. Key elements of SBD.

At the bottom of the center column of Figure 2 are All Other Disciplines, including design of instrumentation and controls, the process, facility and equipment layout, which were viewed historically as not directly relevant to safety and safeguards. Included at the top is the Safety-by-Design process described in DOE STD 1189-2008.[13] Under SBD, all of these elements are complementary and need to be addressed and designed concurrently as part of a single integrated project.

The yellow boxes in the middle are the requirements and specifications that mitigate nuclear security and safeguards threats from both state-level and sub-national groups. In the case of MC&A and physical protection, these design activities are driven by national requirements and regulations. In the case of international safeguards, the design activities are driven by the safeguards agreement(s) between the state and the IAEA, and the IAEA Safeguards Criteria. State agreements with the IAEA are typically based on the model comprehensive safeguards agreement (INFCIRC/153 (corrected)), which specifies safeguards provisions and requirements.[a] The measures relevant to nuclear facility design and construction are nuclear material accountancy, containment and surveillance (C/S), and facility design information examination and verification (DIE/DIV). Other measures and provisions are also addressed, including safeguards inspections, the inventorying of nuclear material, recording and reporting of inventory changes, and the submission of operating and accounting reports, but these are more relevant after the plant begins operation. To successfully implement SBD, it is important that the national regulator, SSAC, and IAEA be brought into the process at an early stage in order to clarify national MC&A, physical protection, and international safeguards requirements. This will necessarily broaden the design team, and will require greater coordination and earlier involvement of these additional stakeholders.

Regarding the design of other proliferation barriers, in principle this is addressed by the nuclear material accountancy, physical protection, and international safeguards measures and elements. However, the term is used here to note that additional design and evaluation of processes and barriers to reduce risk of diversion and theft of nuclear material may be possible during the design stage. The idea would be to engineer features directly into the process or facility design that would make it more challenging to divert nuclear material or misuse the facility, i.e., in support of a clandestine nuclear weapons program. This will be addressed later in Section-4, regarding proposed Safeguards Effectiveness Report (SGER) and the evaluation of safeguards approach options potentially using the Proliferation Risk and Physical Protection (PRPP) assessment methodology.

The right hand column of Figure 2 lists the key elements to implementing SBD. Note that every listed element refers either to activities early in the project, coordination within the project, or coordination between the project team and other stakeholders. The successful implementation of SBD requires the additional coordination of all of these elements for safeguards with the safety design requirements and the other design disciplines.

[a] Three countries, India, Israel, and Pakistan, have safeguards agreements with the IAEA based on the older INFCIRC/66. However, the current trend is for countries to conclude comprehensive safeguards agreements with the IAEA based on INFCIRC/153 (corrected) and to adopt a protocol additional to this agreement based on INFCIRC/540 (corrected).

2. PROJECT MANAGEMENT AND COORDINATION

This section presents and describes in a simplified manner the management and coordination of a typical nuclear facility design and construction project, based on experience in the United States. The design and construction process is broken down into stages and each stage is reviewed and analyzed to determine how it would be affected by the implementation of SBD. In some cases, new requirements or stakeholders would be involved. Consequently, greater coordination with a broader project team would be required. In other cases, activities or input would have to occur sooner than in the current design process in order to implement the requirements in a timely and less disruptive manner. ***Where these impacts are identified, they are highlighted in bolded italics for added emphasis to note that this is a significant departure from the current design and construction process.*** This section builds on the high level framework for SBD presented in the report, "Institutionalizing Safeguards-by-Design: High-level Framework," prepared by the SBD project team in 2008.

According to the Project Management Institute, a project is a *"temporary endeavor, undertaken to create a unique product, service, or result."* [14] In this case, temporary means that the project has a limited duration with a definite beginning and a definite end. In the case of constructing a nuclear facility, the project end is met when the facility has been constructed and tested to demonstrate that it meets all design criteria and specifications. At this stage, the facility is turned over to the facility operator for completion of all the necessary steps to satisfy the regulatory commitments and requirements, training of plant staff, and to begin plant operation. Figure 3 is a simplified project flow diagram, depicting the basic stages of a project, showing the execution of a project from the pre-conceptual design stage to operation of the facility. This figure aligns with that prepared at the aforementioned IAEA workshop, as documented in the report from that workshop, *Facility Design and Plant Operation Features that Facilitate the Implementation of IAEA Safeguards*.[1, 2] Each of these stages will be described in further detail with emphasis on those aspects most relevant to implementing SBD.

Figure 3. Simplified project flow diagram.

According to the High Level Framework Report, ***"Implementation of the SBD process requires the participation of safeguards and security subject matter experts beginning with the pre-conceptual design stage and continuing through the construction of the nuclear facility. They must coordinate closely with other project activities, especially safety, process design, and facility layout."***[1] Prior to operation of the facility, the operator is responsible for ensuring that the facility is fully operational and meets the original design requirements and specifications – including that the safeguards requirements are met and adequate safeguards measures and provisions are in place. The High Level Framework Report states further, ***"The National Nuclear Regulatory authorities and the IAEA must be involved in the SBD process at an early stage to ensure the designer/builders and operators understand the relevant requirements, and to develop a mutually agreed upon timeline of activities."*** [1]

2.1 Pre-Conceptual Design Stage

Activities performed during the pre-conceptual design stage, i.e., project planning stage, include developing the scope, cost, and initial schedule for the project.[b] The project team defines and refines the project objectives, and plans the course of action to meet the objectives. The High Level Framework Report emphasizes, "***The SBD process requires the participation of Safeguards Subject Matter Experts (SMEs) from the very beginning of the concept development, or project planning, phase.***"[1] Figure 4 depicts the components that support the pre-conceptual design stage, with emphasis on those most relevant to the SBD process. It is important to note that the domestic (MC&A) and international (IAEA) safeguards requirements need to be provided to the project team at this early stage. To facilitate the implementation of SBD, the authors propose the creation of a Safeguards Effectiveness Report (SGER) that could be used to define safeguards requirements and criteria, evaluate safeguards approach options for meeting these criteria, and document the performance of the safeguards measures prior to startup of the facility. More will be said about the proposed SGER in Section 4.

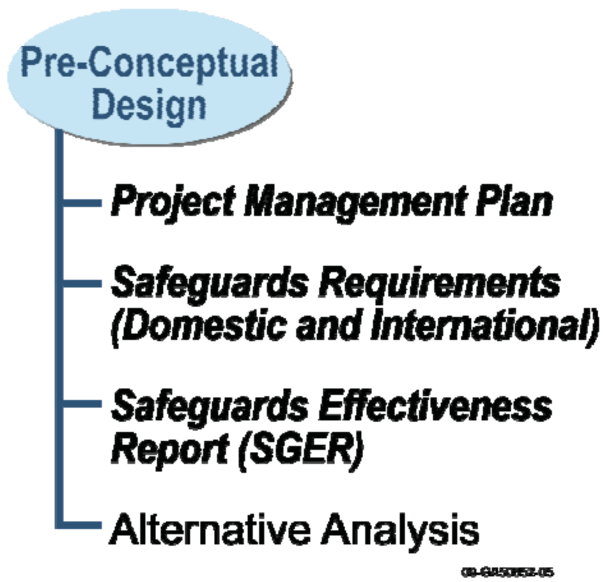

Figure 4. Pre-conceptual design stage.

The Project Management Plan (PMP) is a formal document used by the project manager that defines how the project is executed, monitored, and controlled. It defines what activities are to be performed, by whom, and in what relationship to other project work. According to the High Level Framework Report, "***The PMP must capture the interaction of the project with the activities of the stakeholders in the SBD process. It must address the schedule of stakeholder activities, required stakeholder inputs, required responses to stakeholder inputs, etc. In the case of a complex nuclear facility project, there are many stakeholders, and it will be a vital task to negotiate a coordinated schedule and reflect this in the formal project structure.***"[1]

During the pre-conceptual stage, the scope of the project, including the type and size of the facility to be constructed and its operational characteristics, is evaluated, developed, and documented. The numerous requirements that apply to the project are identified and documented during this stage of the project. These include those of the owner, regulators, designer, and other stakeholders.

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[b] This stage of the project corresponds to the "Initiation Phase" of a Capital Asset Acquisition project, as specified in DOE Order 413.3A.

The national regulator and SSAC implement domestic safeguards regulations, with the SSAC acting as the national point of contact with the IAEA for implementing international safeguards.[15] International nuclear safeguards requirements follow from the international safeguards agreement concluded between the country and the IAEA, pursuant to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT).[6, 16] Countries that have not signed the NPT have concluded international safeguards agreements in accordance with the older INFCIRC/66.[17] Additional safeguards requirements are imposed by the IAEA Safeguards Criteria and Subsidiary Arrangements to the safeguards agreement, including the Facility Attachment (FA), which is prepared for each facility by the IAEA, with input from the SSAC and facility operator.[18] Many of the national nuclear material control and accounting needs and requirements are similar to international safeguards requirements, although coordination with national regulatory authorities and the IAEA is required to ensure the needs of both are met.

Alternative analyses, which are often included in a feasibility study, are performed during the pre-conceptual stage to evaluate options for the facility's design, construction, and operation and the impacts on the options of the safeguards and security requirements that will be applied. Relevant to this, the High Level Framework Report states, "***Inputs to the alternative analyses relevant to the safeguarding of the facility include lessons learned and best practices from facilities that are similar in construction and operation. Alternative strategies evaluated for meeting safeguards requirements include: (1) the use of "off-the-shelf" safeguards measures, (2) research and development needed to enhance existing measures/develop new measures, and (3) design changes to provide intrinsic measures. Systems engineering is used during this activity to ensure the proper integration of safeguards requirements into the facility design***" [1] The systems engineering approach ensures an integrated approach among the various project disciplines, such as safety, process design, facility layout, etc.

In the case of a nuclear weapons state, the conclusion of this stage is the point at which the state may choose to place the facility on the Eligible Facilities List (EFL) for potential random selection for inspection by the IAEA. In accordance with established policy in nuclear weapons states, all civil and most other nuclear facilities are included on the EFL, unless the facility is specifically involved in a national defense activity or mission. In the case of a non-nuclear weapons state, this is the point for notifying the IAEA of intention to build the facility. As the High Level Framework Report emphasizes, ***"Earlier notification to the IAEA and submission of preliminary safeguards-relevant design information facilitates an earlier discussion with the IAEA, with potential attendant benefits."*** [1]

Regarding the SGER, ***a first draft of this report should be developed by the project team during the pre-conceptual design stage, and it should be continually updated in each successive project stage.***

2.2 Conceptual Design Stage

Conceptual design is an iterative process to define, analyze, and refine project concepts and alternatives.[c] This process uses a systems methodology that integrates project requirements, identifies and analyzes risks, and explores concepts to evolve a cost-effective preferred solution to meet the project need.[19] Figure 5 depicts some of the key components to support the conceptual design stage of the project, with emphasis on those most relevant to SBD. It is important to note that while some of these documents are initially created before or during conceptual design, they may not be finalized until much later in the project (e.g. the SGER).

[c] This stage of the project corresponds to the "Definition Phase" of a Capital Asset Acquisition project as specified in DOE Order 413.3A.

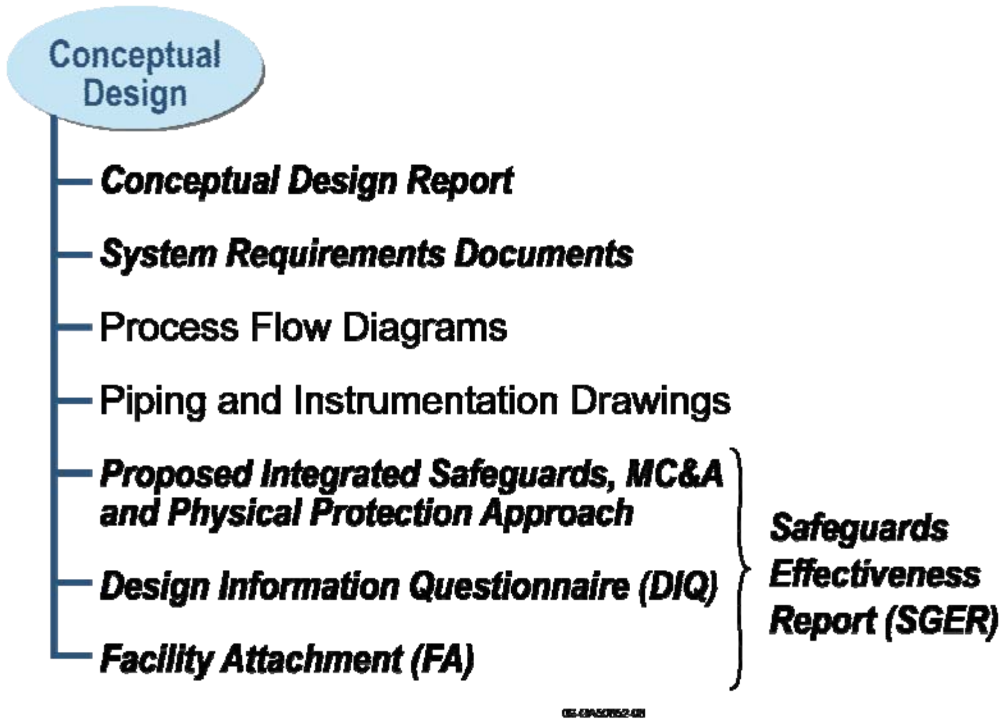

Figure 5. Conceptual design stage.

Documents that are critical to the definition, control, and execution of the project are created and approved during this stage and include, but are not limited to:

- ***Conceptual Design Report (CDR)***
- Conceptual Cost Estimate
- ***System Requirements Documents (SRDs)***
- Process Flow Diagrams (PFDs)
- Piping and Instrumentation Drawings (P&IDs)
- Facility Layout Drawings
- ***Safeguards Effectiveness Report (SGER)***
- ***Design Information Questionnaire (DIQ)***
- ***Facility Attachment (FA).***

The size and throughput of the facility, as well as a more detailed project scope, are developed and included in the CDR. According to the High Level Framework Report, "***The CDR will address and include the impact of the IAEA and state requirements on the facility scope and the design developed during this stage of the project. Information contained in the CDR and facility layout drawings may be utilized to provide the information included in the DIQ submitted to the SSAC for transmittal to the IAEA, if necessary.***" [1] Information from the CDR, SRDs, PFDs, P&IDs, and facility layout drawings, may also be utilized to provide information to the state as part of their licensing process for the nuclear facility.

SRDs are utilized to document the requirements of the individual systems and in establishing design criteria. PFDs are utilized by the process system designers to show the various process material flows within a process. A P&ID is a diagram in the process industry that shows the piping of the process flow together with the installed equipment and instrumentation. According to the High Level Framework Report, ***"Subject Matter Experts for safeguards, MC&A, and security must be involved in the development of the SRDs, PFDs and P&IDs in order to ensure that the requirements of their areas of responsibility are addressed and integrated into the design of the systems, structures and components. Their participation is essential to ensure proper integration with each other, and safety, such that synergies can be exploited, and any conflicts can be identified and resolved in a timely fashion."*** [1] Once the requirements are identified and included in the formal project management plan, project management and systems engineering activities will ensure that the requirements are addressed in the project in an integrated fashion.

As previously noted, the SGER will define the safeguards requirements and criteria, include an evaluation of the safeguards approach options, and record and document the performance of the safeguards measures and systems in meeting these requirements. The SGER is discussed in more detail in Section 4. ***What is important to note in the SBD process is that the safeguards relevant design drawings and information used by the project team can also be used to produce the SGER, which in turn can be used to complete the DIQ and prepare the draft Facility Attachment (FA).***

While preliminary facility design information is transmitted to the IAEA from the SSAC during the pre-conceptual stage, the actual IAEA Design Information Questionnaire (DIQ) is typically transmitted to the IAEA during the conceptual design stage. The DIQ contains fundamental information regarding the location, identification, size and capacity of the nuclear facility, as well as the process employed, and nuclear material handled therein. The purpose of this information is to provide safeguards relevant information to the IAEA regarding the design, construction, and operation of nuclear facilities to permit the IAEA to verify this information in design information examination and verification (DIE/DIV) activities. The point of this is to allow the IAEA to determine if the nuclear facility is being constructed and operated as declared, and to detect any changes in design or operational status relevant to safeguards. In nuclear weapons states, the DIQ is not submitted until after the facility has been selected by the IAEA from the Eligible Facility List for inspection. ***However, for non-nuclear weapons states, i.e., most other countries, the DIQ must be prepared by the facility operator and transmitted through the SSAC to the IAEA at this stage in the process.***

A Facility Attachment (FA) is prepared for each facility under IAEA safeguards. Typically the draft is prepared by the facility operator and transmitted through the SSAC to the IAEA for review and approval. If the FA lacks adequate information to permit the IAEA to develop a suitable safeguards approach, they may request additional information regarding the facility from the SSAC. Officially, the FA is referred to as a "subsidiary arrangement" to the safeguards agreement between the state and the IAEA. It contains the safeguards relevant technical and administrative information and procedures, and specifies how the provisions of the safeguards agreement will be applied to the facility. The FA tends to be similar for facilities of a given type or similar construction. While the preparation of a FA for an established facility such as a research reactor or nuclear power plant of established design is routine, the preparation of one for a large and complex facility, such as a large-scale fuel reprocessing plant, can take considerable time. ***For such large and complex facilities, the safeguards requirements, FA, and safeguards approach could potentially evolve through design and construction stages up to the point of start-up, before it is finalized. This is of great concern to industry since it introduces uncertainty in the design process if these are not finalized prior to the end of the preliminary design stage.*** More will be said about the minimum safeguards system and infrastructure requirements in Section 4, in the development of the Safeguards Effectiveness Report.

Regarding the FA, the High Level Framework Report states, ***"Discussion with the IAEA and development of the FA is initiated during the conceptual design stage. In practice, the FA is developed with the input of the facility operator and submitted by the national authorities (SSAC) to the IAEA for review and approval.*** [20] ***For facilities of an established design, or 'evolutionary' facilities that are close to existing facilities, conclusion of the FA at an early stage is possible, and preferred by designers/builders to fully understand safeguards requirements imposed on the design."*** [1]

2.3 Preliminary & Final Design Stage

The preliminary and final design stage may be divided into the two segments, respectively.[d] Figure 6 depicts the key documentation that supports this stage of the project.

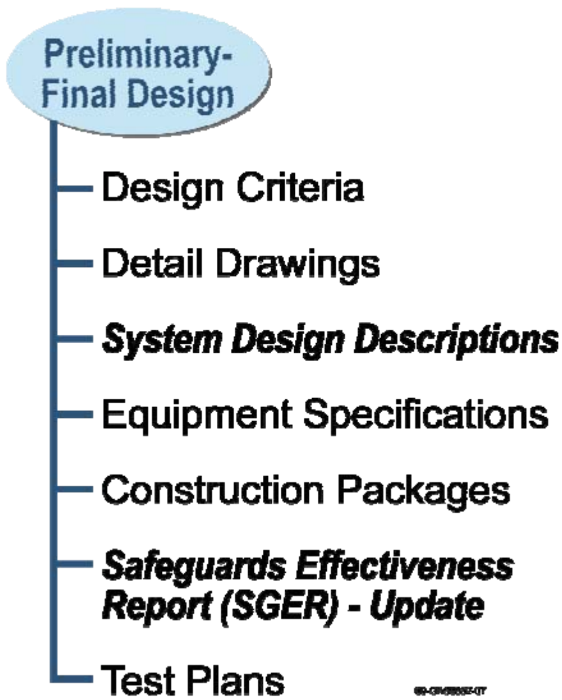

Figure 6. Preliminary-final design stage.

Usually it is in this stage that the facility is adapted to the site specific requirements. A project to adapt an evolutionary or "sister" plant to a new site would typically commence with the final design. It is at this stage where the facility is adapted to site- and owner-specific requirements.

Design Criteria are developed from the SRDs and other design documentation and is utilized in creating the detailed design drawings. The High Level Framework Report recommends that ***"The safeguards subject matter experts participate in the design development for the facility, with a leadership role in the design of the safeguards features, and a review role for all design activities that could affect the safeguards envelope."***[1] The facility designers continue to utilize a systems engineering approach to ensure the integration of safeguards requirements into the facility design. During this stage, the engineering team creates detailed design drawings and equipment specifications, as well as construction packages, including testing and acceptance criteria. System Design Descriptions can be created to describe the systems, structures, and components that are being created as a result of the SBD

[d] This stage of the project corresponds to the first part of the "Execution Phase" of a Capital Asset Acquisition project as specified in DOE Order 413.3A.

process.[1] Test plans are developed for utilization during the construction stage to demonstrate that the systems, structures, and components meet their design requirements.

With the completion of the final design, often referred to as the "baseline" design, a final cost estimate is developed. The High Level Framework Report recommends that ***"A Configuration Control Board (CCB), which includes at least one safeguards SME (in addition to security and safety SMEs), is created in order to ensure that changes to the baseline design are made in a manner that preserves compliance with safeguards, safety, and mission requirements and does not jeopardize cost and schedule performance. Safeguards SME CCB members are responsible for ensuring that all design changes are reviewed to ensure that the safeguards measures and systems have not been adversely affected in their ability to meet the safeguards requirement."*** [1] Members of the plant operation and maintenance organizations utilize the information created during this stage to initiate the development of their procedures for future use, including procedures necessary to ensure compliance with safeguards requirements.

The content of the SGER continues to evolve as the SBD process is implemented, the design matures, and the operational procedures for the facility are further developed. [1]

2.4 Construction Stage

The construction stage covers the time from the initial site preparation work through to the construction of facilities, and the installation and acceptance testing of equipment.[e] Figure 7 depicts some of the activities and documents that support the construction stage of the project.

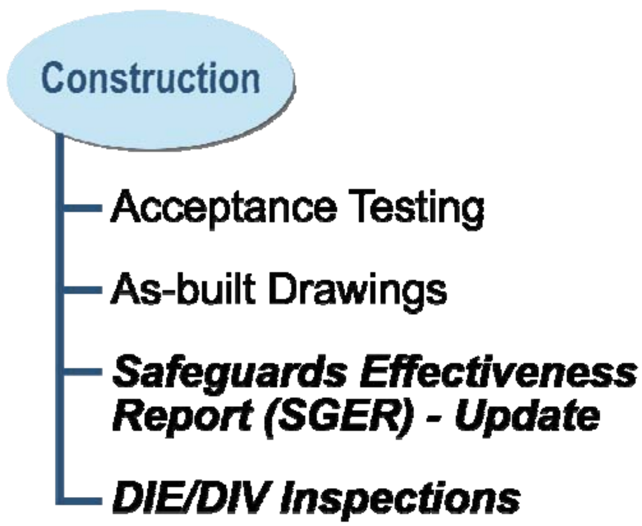

Figure 7. Construction stage.

Safeguards equipment is typically installed during the construction stage of the project, including the following:

- MC&A and physical protection equipment required by the facility operator, or as required under national regulation
- IAEA equipment for the purpose of implementing international safeguards

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[e] This stage of the project corresponds to the second part of the execution phase and the transition/closeout phase of a Capital Asset Acquisition project as specified in DOE Order 413.3A.

- Joint use equipment, used by the national regulator and IAEA or facility operator and IAEA[f, 21]
- Performance and acceptance testing is completed for the:
- Equipment and systems installed for the operation of the facility
- MC&A and physical protection equipment
- IAEA safeguards equipment, including any joint use equipment.

According to the High Level Framework Report, it is recommended that ***"The safeguards SMEs support the acceptance testing performed to validate that the safeguards equipment and systems meet the safeguards performance requirements."*** [1]

During the construction phase, the project Configuration Control Board ensures that proper approvals are obtained for any changes to the "baseline" design. The High Level Framework Report recommends that ***"Safeguards SMEs will participate in the review and approval of field and design changes affecting the safeguards envelope."*** [1] At the completion of the construction, "As-Built" drawings are prepared to represent the actual construction, configuration and installation details. The High Level Framework Report suggests further that ***"Safeguards SMEs will review the detailed as-built configurations to ensure that the safeguards strategies developed and incorporated into the design will meet the safeguards performance requirements."*** [1]

During the construction stage, the IAEA actively performs design information examination and verification activities (DIE/DIV) to verify the correctness and completeness of the design information provided by the state regarding the construction and status of the nuclear facility. An initial DIE/DIV is performed on a newly built facility to confirm that the facility is built as declared.[13] If the facility is very large and complex, such as a spent fuel reprocessing plant, the DIE/DIV activity would be extensive and would require several inspections over many years during the construction of the facility. The activities performed by the IAEA need to be coordinated by the project team to minimize interference with the construction project. The IAEA may also need to access parts of the facility, which may in the future become inaccessible due to high radiation or radioactive contamination, to ensure that they are not used for undeclared processing. Communication between the IAEA and the facility operator through the SSAC is very important during this stage to ensure that the IAEA is able to complete the DIE/DIV activities to verify the declared construction and status of the facility. The IAEA has the continuing right to perform DIE/DIV throughout the life cycle of the facility, although the activities tend to be less intrusive during plant operation. In nuclear weapons states, the DIE/DIV will begin after the facility has been selected from the Eligible Facility List. For most other countries, facilities will be inspected and the design initially verified at the earliest stages, i.e., during excavation.

The facility attachment (FA) was introduced and discussed during the conceptual design stage. As previously noted, if the facility is an established design or type, then the operator may provide input for the draft FA based on similar facilities. As a consequence, the draft FA may be prepared during the conceptual design stage. If however, the facility is large and complex, such as a spent fuel reprocessing plant, then the FA may continue to evolve during the design and construction of the nuclear facility. In this regard, according to the High Level Framework Report and feedback from industry, ***"The nuclear industry has provided input that they would prefer that the safeguards approach and Facility Attachment be finalized relatively early in the design process – by the end of preliminary design which is probably possible for nuclear facilities of established process and design. However, for new processes and facilities, the FA may need to evolve to incorporate changes during testing, commissioning and start-up of the facility."*** [1] From this it is clear that the IAEA, SSAC, and facility

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[f] While in principle, the joint use of equipment for safeguards purposes holds the promise of greater efficiency and economy due to cost sharing, it is restricted under IAEA Safeguards Department, SGTS/TIE Policy #20.

operator must be in close coordination regarding the preparation of the facility attachment, and ideally at an early stage. If the IAEA needs additional information from the facility operator to approve the FA, then the facility operator needs to know this as soon as possible.

The SGER was also introduced during the conceptual design stage. According to the High Level Framework Report, it is recommended that ***"The SGER be revised to reflect any changes that must be incorporated as a result of the construction of the facility and the further development of the planned operation of the facility."*** [1]

2.5 Facility Operation

Following the completion of construction activities and the successful completion of acceptance testing, the facilities are transferred to the operator. Figure 8 depicts key activities that occur at this stage.

During the early commissioning stages of plant operation, the effectiveness and performance of the safeguards and physical protection systems would be tested under actual "hot" conditions, using typical plant feed and materials, rather than cold streams or surrogates. The performance of the safeguards and physical protection systems would be evaluated and documented in the proposed SGER. It is also envisioned that this would be necessary to demonstrate to the national regulator that these systems will perform as expected. At this stage, the SGER would be updated and finalized, including all of the safeguards documentation, evaluations, and analysis relevant to the design and construction of the nuclear facility and its safeguards systems.

With the successful completion of the operational readiness review, the regulator provides the operator with the authorization to begin plant operations. Equipment installed by the facility operator to meet national MC&A, safety regulations, and physical protection requirements is maintained and controlled by the operator. IAEA safeguards equipment and systems are operated and maintained by the IAEA. However, in the case of joint use equipment, the maintenance will be performed as agreed between the facility operator, SSAC, and the IAEA. From the perspective of the IAEA, in the case of joint use equipment, it is essential that they be able to base their nuclear safeguards conclusions independently of the facility operator and national authorities (SSAC). This need for drawing independent conclusions can complicate the sharing of equipment for safeguards purposes. These issues need to be resolved prior to the design, construction, and operation of the facility.

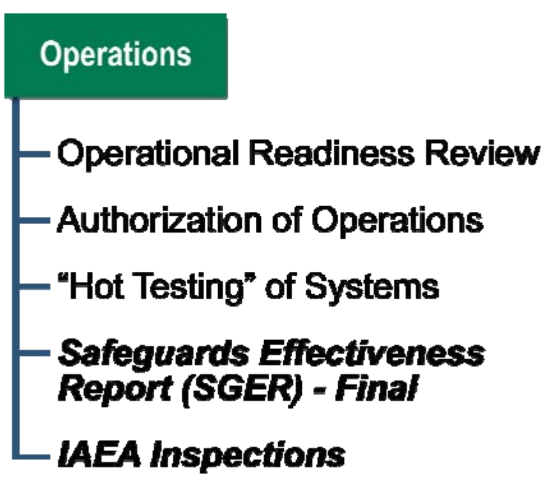

Figure 8. Facility operation.

During the ongoing operation of the facility, separate inspections are performed by the national regulator and the IAEA. In nuclear weapons states, IAEA inspections will be performed in accordance with the IAEA Safeguards Criteria, and/or state level safeguards approach (SLA), if the facility has been selected from the Eligible Facility List by the IAEA. For most other countries, the facilities will be inspected routinely in accordance with the IAEA Safeguards Criteria and/or state level safeguards approach. For facilities handling plutonium or highly enriched uranium, IAEA safeguards inspections may be as frequently as monthly. For facilities such as research reactors and nuclear power plants, IAEA safeguards inspections may be quarterly or annually, depending on the size of the reactor, amount of nuclear material handled, and state level safeguards approach. The IAEA may also perform short notice random inspections (SNRI), no-notice inspections, and Complementary Access (CA) under the Additional Protocol, as negotiated between the state and IAEA.

During plant operation, the IAEA will continue to re-verify plant design information and operating status by performing periodic DIE/DIV activities, to confirm the continued validity of the design information and safeguards approach. The IAEA's authority for performing DIE/DIV is a continuing right throughout the facility's life cycle until the facility has been decommissioned for safeguards purposes.[13] Any safeguards relevant changes made by the facility operator to the facility, or mode of operation, need to be declared by the facility operator through the SSAC to the IAEA.

During operation, the plant operator submits to the SSAC regular nuclear material inventory change reports (ICR), material balance reports (MBR), and physical inventory listings (PIL), for the nuclear material handled and stored at the facility. These are then reviewed and confirmed by the SSAC, and forwarded to the IAEA, as per the safeguards agreement.

3. LIFE-CYCLE COST ANALYSIS

As envisioned, a major benefit of SBD is the potential for significantly reducing the cost of implementing safeguards over the life of a facility. Consequently, consideration of facility life-cycle costs and trade off analyses should be performed using systems engineering methods. This is also needed to inform decisions involving the trade off between the capital costs for intrinsic design features for safeguardability and operational costs associated with conducting and supporting safeguards activities (i.e., safeguards inspections, inventory taking, sample taking, preparation of records and reports, equipment maintenance, cleaning out process lines for inventory taking, etc.) Life-cycle cost estimation is the tool used by industry and government to properly account for the cost of safeguards measures and other features through the life of a facility. The scope and scale of these activities will vary, depending on the safeguards approach and safeguards measures utilized. Detailed cost estimation will require input from the IAEA, since they will have up-to-date costs for typical safeguards activities. While the cost estimation activity is important for comparing safeguards approach options and measures, it is important that the safeguards approach and methodology, as envisioned by the plant designers, be discussed with the IAEA to confirm that it would be suitable for implementing international safeguards.

According to the U.S. DOE Guide, *Life-Cycle Asset Management,* life-cycle cost analysis is the systematic, analytical process of evaluating alternative courses of action early on in a project, with the objective of choosing the best alternative to employ scarce resources.[22] The goal is to take into account the true costs of project alternatives, allowing a valid comparison of different options over the operating life of the facility. Because of the typical long life span of nuclear facilities (on the order of 50 years), decisions made early in the process can have a large impact on the costs over the life of the facility. See Figure 9 below from DOE Guide 430.1-1, which shows that approximately 70% of the total life-cycle cost is committed by the end of conceptual design.

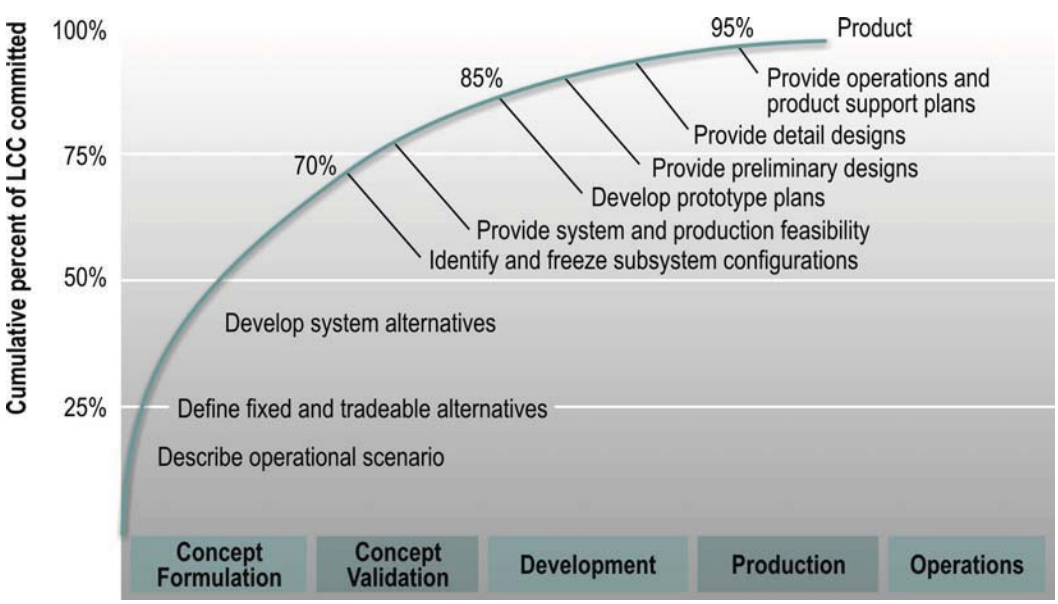

Figure 9. Commitment of life-cycle cost (LCC) by project stage (source: U.S. DOE G-430.1-1)

Life-cycle cost analysis provides a structured method for making more accurate and consistent comparison of the lifetime costs of alternative approaches to meeting project requirements. According to the *Systems Engineering Handbook*, life-cycle cost analysis involves:[23]

1. Obtaining a complete system definition, including elements and subsystems
2. Determining the total number of units needed by the elements and subsystems
3. Obtaining the expected life cycle schedule (i.e., the planned timeframe for design, construction, and operation)
4. ***Obtaining manpower estimates for each phase of the <u>entire</u> program***[g]
5. Obtaining expected overhead and burden rates
6. Developing cost estimates for each subsystem

Regarding item #6, the analyst should make every effort to produce an accurate cost estimate, as opposed to a simple relative estimate. Choosing to reduce the accuracy of this estimate, in the interest of expediency and budget savings, introduces project risk.

There are many methods by which to produce the cost estimate, which include:

1. Expert judgment – typically provided by consulting experts, but which may lack consistency and uniformity
2. Top/down - development of project costs by starting with the high level project characteristics
3. Bottom/up - a summation of the cost contribution for each component of each subsystem at the lowest level.

Each should be used as appropriate, as additional detail is developed during the design of the facility.

The key to a credible estimate is having an understanding of the characteristics, system design features, and technologies to be included in the design.[24] ***Early and complete documentation of requirements and full integration of the design team, as proposed in SBD, is also the key to successful life-cycle cost analysis and estimation.***

The application of safeguards to a nuclear facility impacts the life-cycle cost of the facility. Firstly, the facility has to be designed and operated in compliance with the MC&A and physical protection requirements imposed by the national regulator. This requires that the facility allow for the physical protection and accountancy of the nuclear material. This means that space must be provided for equipment, operational procedures must consider safeguards requirements, plant operations must allow for accounting activities (e.g. inventory taking), and operations staff must be provided to support the safeguards activities. Secondly, the facility has to be designed and operated such that international safeguards can be applied. Independent verification by the IAEA will require additional equipment, space, and infrastructure. Accommodations for the authentication of joint use equipment will be required. Operations may need to slow or stop to allow IAEA safeguards inspections, and personnel will be required to provide information and support to the IAEA activities, as coordinated through the SSAC. These costs are part of the "cost of doing business" for a nuclear facility and are typically borne by the facility owner/operator, although some states may reimburse the owner/operator for costs associated with the implementation of IAEA safeguards. Regardless, it is in the best interest of the owner/operator to minimize these costs over the life of the facility, using life cycle cost analysis. As illustrated in Figure 9, this process needs to begin early in the design process.

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g. The INCOSE Handbook makes the point that manpower estimates are especially important for the operations phase of a project.

Application of the SBD process to the design, construction, and operation of a nuclear facility emphasizes early and complete integration of safeguards with the balance of the project. A primary result is that the safeguards requirements are included, and design alternatives for safeguards measures are developed, early in the project. Thus, the cost of safeguards measures and activities can be readily and accurately incorporated into the project alternatives and life-cycle cost analyses. This provides an opportunity to reduce the cost and time impacts of providing for and supporting safeguards activities. The main elements involve:

1. Identification of design measures that will be necessary to meet safeguards regulations (i.e., equipment, lab space, or accessibility to verify design features)
2. Identification of intrinsic design features that increase the safeguardability of the facility and potentially reduce or eliminate the need for some safeguards measures
3. Analysis of the costs of extrinsic activities to accomplish safeguards objectives versus the capital costs of incorporating intrinsic safeguards features in the facility design
4. ***Early negotiation of the draft facility attachment and proposed safeguards approach with the IAEA, commencing as early as the conceptual design stage, to confirm that the design will meet the international safeguards requirements.***[5]
5. Consideration of IAEA needs in the design and operation (e.g., joint-use equipment challenges, C/S placement and needs, and capacity to perform DIV)
6. Minimization of the impact to plant operations to meet safeguards requirements and accommodate safeguards activities
7. Minimization of the cost and schedule risks associated with facility re-design and re-work to meet safeguards requirements.

Including life-cycle analysis as part of the SBD process may also yield cost savings for the IAEA and SSAC. Potential cost savings may result from the following:

1. Early consideration of joint use equipment - provided that data authentication issues are adequately addressed
2. A facility design that lessens the operational impact of safeguards activities - (i.e., a design that allows the safeguards to be performed more efficiently with less inspector time spent in facility)
3. A facility design that readily accommodates IAEA needs - (i.e., requires less IAEA interactions, fewer cameras, or potentially fewer measurement points to verify nuclear material inventory and flow)
4. Capability to perform verification using unattended and remote monitoring.

Life-cycle analysis of a nuclear facility, increasing in detail in parallel with increasingly specific design detail, allows the consideration of design, construction, and operational alternatives to take into account the true cost of design decisions. It encourages identification and proper consideration of the cost of intrinsic safeguards features in comparison to extrinsic activities to meet the same regulatory requirements. Improved cost estimates that include safeguards requirements, in combination with early approval of safeguards design strategies by the national regulator and IAEA, reduce the project cost and schedule risk. This is because time consuming and costly facility rework to accommodate safeguards requirements is minimized. Finally, the owner/operator stands to optimize their cost to plan for and accommodate the operational impact of safeguards activities, as required by the national regulator and the IAEA. This optimization may reduce the operating and inspection costs for the IAEA as well.

4. DEVELOPMENT OF THE SAFEGUARDS EFFECTIVENESS REPORT (SGER)

The proposed SGER is intended as a report that describes the planned safeguards strategy and approach and demonstrates that it will meet the requirements established by the IAEA and the state. The SGER is expected to be a living document, beginning at a high level in the earliest project phases, developing the safeguards strategy, and taking on increasing detail and scope as the design progresses. As requirements and success criteria evolve and mature, this document is envisioned to also contain the analysis that documents that the safeguards design meets the safeguards performance criteria. The required format and content of this report should be determined by industry, the national regulator, and the IAEA, to make certain that it will efficiently address the needs of the major stakeholders.

The SGER would provide the information required for an initial evaluation of the safeguard measures to be used in the new facility by the SSAC and the IAEA based upon: 1) compliance with prescriptive requirements (e.g., establishment and location of key measurement points, physical barriers, or containment/surveillance system performance, provisions for IAEA DIE/DIV activities, etc.); 2) predicted values for performance metrics (e.g., measurement accuracy for safeguards systems, limit of error on material unaccounted for (MUF) estimates, probability of detection, timeliness for detecting diversion), and 3) commitments to establish and implement safeguards program elements (e.g., frequency of safeguards inspections and other safeguards activities).

The SGER would also evaluate safeguards measures and approach options for the facility designer to propose the optimum safeguards approach, relative to defined requirements. In so doing, there may be a role for the Proliferation Resistance and Physical Protection (PRPP) assessment methodology. The PRPP methodology was originally developed in support of the Generation-IV International Forum, next generation nuclear energy system, to evaluate the relative proliferation resistance and physical protection robustness of nuclear facilities.[25] The PRPP analysis methodology could be potentially developed for aiding designers in evaluating, comparing, and optimizing safeguards measures and approaches. In developing PRPP for this purpose, designers would also be building on the assessment methodology used by the International Project of Innovative Nuclear Reactors and Fuel Cycles (INPRO).[26] However, the utility of PRPP for the detailed comparison and evaluation of safeguards measures and approach options, in the design of a nuclear facility, needs to be further demonstrated.

As discussed at the conceptual design stage, the SGER should contain the information to be provided in the DIQ and facility attachment, but at the conceptual design level. This information could be used by the facility operator to submit the initial DIQ and prepare the draft facility attachment.

The SGER would also describe the proposed high-level safeguards strategy and the proposed approach to integrating safeguards, MC&A, and physical protection. This information would be provided to the national regulatory authority. The specific format and content requirements for the high-level safeguards strategy and the proposed approach to safeguards, MC&A, and physical protection should be established by the SSAC in coordination with the IAEA. The SGER provided at the conclusion of conceptual design would identify any safeguards measures or elements of the safeguards strategy where research or development is required in order to meet required performance standards (e.g., a measurement system with specified precision better than the current state of the art). For such measures or elements, the report would also describe briefly the research or development activities planned and alternative approaches developed to address the contingency that the research or development activities might not succeed. The IAEA and national regulator would review the SGER with the designer/operator to make certain that the new facility would be capable of meeting the IAEA safeguards and national MC&A, and physical protection requirements.

As the design matures, the facility owner/operator would update the SGER to reflect the increasing maturity of the design and more precise understanding of the detailed operation of the facility. Depending upon the design and construction approval process, and the needs of the national regulators and IAEA, ***an updated SGER might be provided at various times during the design and construction process. A logical scenario would be to update the SGER at all stages of the design and construction process, analogous to what is currently done in implementing the Safety-by-Design process.***

The portion of the SGER that addresses national requirements would provide the information for the various MC&A and physical protection licensing documents required by the national authorities - (e.g., MC&A plan, physical protection plan, and Vulnerability Assessment). The review, negotiation, and approval process for these updates to the SGER could be performed in a manner analogous to that employed currently by the IAEA and SSAC for the review and approval of the DIQ, FA, and MC&A and physical protection licensing documents, respectively. The format and content of the SGER is expected to evolve as SBD is implemented. It is expected that industry will adopt the approach that best fits within their existing design processes and documentation. The authors believe that the content of the SGER could simply be generated from existing documents used during the current design and construction process for nuclear facilities. ***The primary benefit of the SGER is that it would gather all of the safeguards relevant information for the design and construction of a nuclear facility in one convenient place, subject to the overview of the facility owner/operator, national regulator, and IAEA. It would also more effectively track the evolution of the safeguards approach and measures, including physical protection, and document clearly how the designer plans to meet these requirements.***

5. IAEA LED INTERNATIONAL INITIATIVE TO DEVELOP SAFEGUARDS-BY-DESIGN

The IAEA hosted an international workshop entitled "Facility Design and Plant Operation Features that Facilitate the Implementation of IAEA Safeguards" in October 2008 in Vienna, Austria. The workshop was well attended by representatives from IAEA Member States, the European Commission, the nuclear industry, national government agencies, and from various departments in the IAEA.[2] Of relevance to this report is that the IAEA workshop attendees supported the general idea of the Safeguards-by-Design process. The proceedings of this workshop are documented in Reference 2. Excerpts and quotations noted below are taken from this reference. The prospective roles and activities of the facility designer, operator, SSAC, and IAEA during the design, construction, and operation of a nuclear facility were captured by the workshop participants as shown in Figure 10 below.

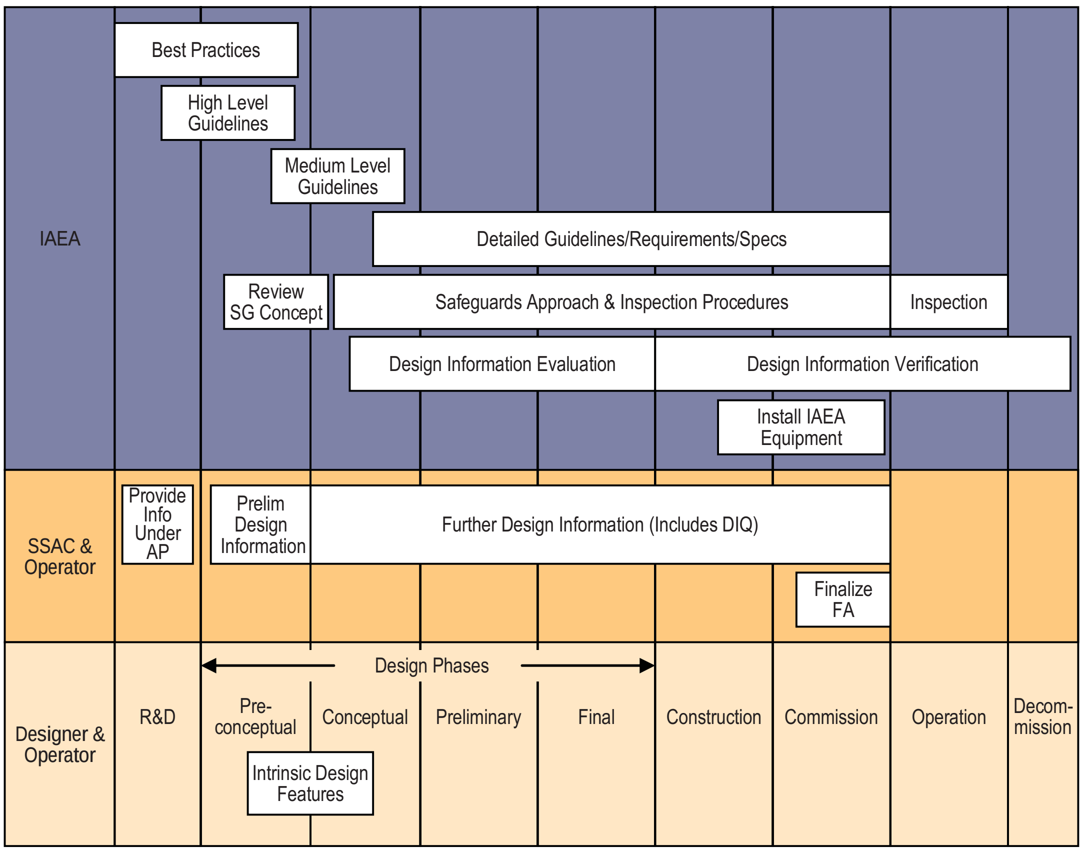

Figure 10. Activities timeline for IAEA proposed SBD process

The IAEA has a clear mandate to apply international nuclear safeguards through safeguards agreements with Member States concluded pursuant to the NPT, by employing monitoring and verification. However, at this stage, the IAEA's role in the implementation of international nuclear security and safety is largely advisory rather than direct verification. Recognizing this distinction, the IAEA workshop participants focused on IAEA safeguards, in particular, when they defined a proposed "IAEA SBD" process as *"an approach wherein safeguards are fully integrated into the design process of a nuclear facility - from initial planning through design, construction, operation, and decommissioning."* The IAEA defines safeguards as "*the means applied to verify a state's compliance with its undertaking to accept an IAEA safeguards agreement on all nuclear material in all its peaceful nuclear activities, and to verify that such material is not diverted to nuclear weapons, or other nuclear explosive devices.*"

From the IAEA's perspective, SBD is expected to improve the efficiency and effectiveness of safeguarding new nuclear facilities by: reducing the time and cost of the inspection effort at the facility, incorporating data authentication, use of process monitoring in the safeguarding of selected facilities, facilitating the joint-use of equipment and instrumentation between the operator and the IAEA, minimizing facility retrofit for safeguards equipment, and by incorporating flexibility in the facility design for safeguards equipment and needs.

Workshop participants suggested that once sufficient early design information has been provided, the facility owner/operator or the IAEA can propose nuclear material balance areas (MBAs), based on the facility design, nuclear material flows and composition, and IAEA quantity and timeliness goals (for detecting a diversion of nuclear material). For each MBA, both the facility operator and the IAEA must be able to independently close the material balance and evaluate any difference between the beginning and ending inventory. The workshop participants strongly endorsed the integration of safeguards into the design of new facilities earlier than is presently done, with collaborative participation by the IAEA, in accordance with the ideal process as proposed in Figure 10. The intent of the timeline proposed by the IAEA workshop participants is to foster an early and collaborative approach to develop the safeguards approach and the facility attachment. ***Subsequent to this workshop, industry stressed the need to reach full agreement on the safeguards approach by no later than the end of the preliminary design stage since this is the point at which the layout and infrastructure are frozen, and detailed (final) design commences. This is even earlier than considered at the IAEA workshop, and is an important point to be resolved in future discussions between industry, state regulators and IAEA.***

Additional recommendations from workshop participants included:

- Revising the *IAEA Safeguards Manual* to take account the SBD initiative
- Providing IAEA safeguards requirements to facility designers at the earliest stage
- Creating expert working groups tasked with defining the SBD process
- Creating an implementation strategy
- Developing new design guidelines, based on facility type, that can be published as part of the *IAEA Nuclear Energy Series*
- Proposing SBD process timelines for nuclear facilities in various stages of development (e.g., new, evolving, or established design).

Anticipated benefits from this process included:

- More clearly defined safeguards vision and guidelines
- More readily available safeguards guidelines to enable compliant and/or optimized plants to be built with minimal impact on the operator and designer/constructor
- Minimized impacts on plant operation to accommodate safeguards activities
- Improved plant capability for maintenance and unattended operation
- Greater awareness of facility operators of the next generation safeguards systems
- Improved integration of safeguards with safety and security
- More timely input from the IAEA to avoid later facility retrofit
- More timely verification and authentication of safeguards signal transmission (for joint use instruments)

- More effective stakeholder engagement in the design phase, minimizing changes during construction.

As discussed at the workshop, the IAEA would develop a safeguards approach that includes nuclear material flow and inventory key measurement points, and other strategic points in the facility, as well as the measurement and monitoring equipment to implement the approach. The negotiation between the three major stakeholders to finalize this approach could potentially result in an optimum combination of safeguards measurement and monitoring systems including:

- Fully independent IAEA equipment
- Joint use equipment, used by the IAEA and facility operator or SSAC

In all cases, this equipment would need to be integrated into the project management scheme to ensure that cost, schedule, and performance requirements are met, including the requirement for the IAEA to be able to make independent safeguards conclusions regarding the facility and nuclear material therein.

6. CONCLUSIONS AND RECOMMENDATIONS

The objective of the NNSA sponsored development and support of SBD is to achieve universal adoption and implementation of the SBD approach in new nuclear projects around the world, in order to make new nuclear facilities safer, more secure, and easier to safeguard. Work is required in a number of vital areas to make this happen. It will be necessary to develop safeguards requirements and success criteria that provide the designers with the flexibility to meet the safeguards requirements. The design toolkit needs to be augmented with further developments in technology and methodology to enable more efficient and effective safeguards, and to provide the designers with the tools needed to assess safeguards performance against success criteria. Included in the toolkit would be design guidelines for the safeguarding of different facility types, and documented safeguards relevant lessons learned from previous projects. The approach to project management and coordination of the design process needs to be adapted to accommodate the changes required for SBD. Institutionalization of all of these elements by the stakeholders in the process, including industry, facility owner/operators, national regulators, and the IAEA, is needed to make SBD the standard approach. Ensuring that all of the required elements are developed in such a way as to be practical and beneficial to all stakeholders will determine whether SBD can be widely implemented.

This study focused on the project management and coordination aspects of the SBD approach. Other studies performed during 2009 under NNSA sponsorship have focused on the development of requirements and on the design toolkit, in the form of safeguards guidelines for designers of nuclear facilities. The present report includes an example project, and identifies the safeguards activities within the context of the project. The authors expect industry to develop their own approaches to incorporating SBD into their projects, if motivated to do so by cost reduction, or to meet requirements. The purpose of this discussion is to present the project management and coordination methodology to the broader international safeguards community, and to familiarize nuclear project managers with the idea of SBD. The authors hope it can serve as a foundation for discussions between stakeholders as they collaborate to develop a mutually agreed timeline and methodology for implementing SBD.

Some argue that SBD is a problem of properly defining workable performance requirements and success criteria. Others argue that it is a design problem. Still others argue that SBD is principally a project management issue. In fact, each is essential, and SBD cannot be implemented if any of these vital elements are ignored.

In the short term, SBD has the immediate potential to reduce cost, performance and schedule risks, and to avoid the costly retrofitting associated with the late development of the safeguards approach and installation of the necessary safeguards equipment. In essence, this would amount to simply avoiding the costs and risks associated with late consideration of safeguards.

The greater potential of SBD is in the longer term, with mature performance requirements, success criteria, and a design toolkit capable of accurately assessing safeguards performance. In this future world, SBD has the strong potential to enable the development of more efficient and effective safeguards approaches and incorporation of intrinsic design features to enhance safeguards. This future holds great potential to develop and exploit synergies from the concurrent consideration of safety and security with safeguards, and vice-versa. This integration warrants serious future attention and development.

This report has focused on the project coordination aspects of SBD. The authors have focused on nuclear safeguards, and in this report have not yet considered the detailed integration with security and safety that they believe to be essential for fully implementing Safeguards-by-Design in the long term. However, the integrating process is foreseen to be analogous, although it will broaden the size of the design and construction project team, and involve more regulators. Regardless, the authors believe that this is the ultimate goal so that new nuclear facilities will be safer, more secure, and more easily safeguarded.

Based on input from the sponsor of this study, special consideration was given to two special aspects associated with SBD – life-cycle cost analysis and the content and development of the proposed SGER. A brief summary of the "IAEA Workshop on Facility Design and Plant Operation Features that Facilitate Implementation of IAEA Safeguards" was also presented, to show how the idea of Safeguards-by-Design is also being driven and supported by the broader international safeguards community.

From the foregoing discussion, the principal conclusions from this study are as follows:

- **The successful implementation of SBD is principally a project management challenge.** Immediate benefits can be obtained through the incorporation of the key elements of SBD and timely and well coordinated interaction of stakeholders, using an agreed project timeline.
- **Input from the nuclear industry indicates that the safeguards requirements, facility attachment, and safeguards approach should be defined early in the design process - perhaps as early as the preliminary design stage**. However, for large and complex nuclear facilities the facility attachment and safeguards approach often continue to evolve before they are finalized prior to start-up of the facility. This indicates that the facility operator, national regulator, and IAEA need to communicate at an earlier stage in the design process to define and resolve issues relevant to the design and incorporation of safeguards relevant features.
- **Life-cycle cost (LCC) analysis can be a useful tool in safeguards design for examining the cost trade-offs** associated with the capital costs of intrinsic design features for safeguardability, versus the later operational costs (including IAEA verification activities). This will only work, however, if the facility owner/operator addresses IAEA costs when they perform the LCC analysis. At present there is no motivation to do so. This warrants further examination.
- **The use of a Safeguards Effectiveness Report (SGER) is proposed to document safeguards requirements, criteria, specifications, and performance evaluations for safeguards systems during the design and construction of nuclear facilities**. It is intended to be a living document that would contain increasing detail about safeguards measures and activities as the design matures. The primary benefit of the SGER is that it would gather all of the safeguards relevant information for the design and construction of a nuclear facility in one convenient place, subject to the overview of the facility operator/owner, national regulator, and IAEA. It would also more effectively track the evolution of the safeguards approach and measures, including physical protection, and document clearly how the designer plans to meet these requirements.
- **The content of the SGER could be used to complete the IAEA design information questionnaire (DIQ) and draft facility attachment (FA) for the respective facility.** This document would also serve to further integrate safeguards, safety, and physical protection during the design process.
- **The SGER would include a section regarding the evaluation of various safeguards measures and approaches to meet these criteria**. In this regard, there is a current need for an evaluation methodology for comparing and evaluating safeguards measures and approach options, relative to defined requirements. The Proliferation Resistance and Physical Protection (PRPP) analysis methodology has the potential to be used by the facility designer to compare, evaluate, and optimize safeguards measures and approach options. However, further development and demonstration of the PRPP methodology in this role is necessary.

- **The SGER should identify the minimum installation requirements and specifications for safeguards related equipment and systems**. As a minimum, these should include: i) space requirements, ii) utility requirements, including electrical mains and emergency backup power, iii) data transmission requirements, including special communication protocols or tamper resistance, and iv) cable and pass-through port penetrations. Knowing this information at an early stage (i.e., no later than the end of the preliminary design stage), would minimize costly facility retrofits to accommodate safeguards systems during or after facility startup.

Further work is required in a number of areas. The authors note that other studies supported by the Next Generation Safeguards Initiative (NGSI) are addressing the development of requirements and performance criteria, as well as contributing to the design toolkit through the development of technology, methodology, and safeguards guidelines for designers.

To further develop the SBD process, the authors recommend the following to NNSA:

- **In the short term, conduct a domestic workshop with representatives from the nuclear industry** to ensure that their perspectives and needs are factored into further development of the SBD process. [High priority and vital to successful implementation]

- **In the short term, provide relevant SBD project reports to the IAEA, and support them in hosting a second international SBD (3S) technical workshop** to be attended by representatives from IAEA Member States, industry, national regulatory authorities, and other stakeholders (e.g. facility designer/builders, owner/operators, etc.). [High priority and vital to successful implementation]

- **In the medium term, continue to support the demonstration of the SBD process in the design and construction of the DOE Next Generation Nuclear Plant (NGNP)** through to the completion of the preliminary design. The NGNP is a U.S. DOE led project with industrial partners, to design and license a high temperature gas cooled reactor (HTGR). Conceptual design of the NGNP is expected to begin in the spring of 2010. [Moderate priority]

- **In the longer term, consider the use of SBD in other DOE projects**. [High priority if SBD is to be implemented within DOE]

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