IAEA Nuclear Energy Series

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International Safeguards in the Design of Nuclear Reactors

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INTERNATIONAL SAFEGUARDS IN THE DESIGN OF NUCLEAR REACTORS

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world''.

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FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world." One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6 of the IAEA Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property". The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

This publication, is principally intended for designers and operators of nuclear reactor facilities; however, vendors, national authorities and financial backers can also benefit from the information provided. It is introductory rather than comprehensive in nature, complementing the Guidance for Implementing Comprehensive Safeguards Agreements and Additional Protocols, IAEA Services Series No. 21, and other publications in that series. This guidance will be one in a series of facility specific safeguards by design guidance publications that complement the general considerations addressed in the publication International Safeguards in Nuclear Facility Design and Construction, Nuclear Energy Series No. NP-T-2.8.

Safeguards by design is the process of including the consideration of international safeguards throughout all phases of a nuclear facility project, from the initial conceptual design to facility construction and into operations, including design modifications and decommissioning. The 'by design' concept encompasses the idea of preparing for the implementation of safeguards in the management of the project during all of these stages. Safeguards by design does not introduce new requirements but rather presents an opportunity to facilitate the cost effective implementation of existing requirements.

IAEA safeguards are a central part of international efforts to stem the spread of nuclear weapons. In implementing safeguards, the IAEA plays an independent verification role, which is essential for ensuring that States' safeguards obligations are fulfilled. A great majority of the world's States have concluded comprehensive safeguards agreements with the IAEA pursuant to the Treaty on the Non-Proliferation of Nuclear Weapons that detail these obligations, and many have also signed a protocol additional to that agreement.

It is in the interest of both States and the IAEA to cooperate to facilitate the implementation of safeguards, as this cooperation is explicitly required under comprehensive safeguards agreements. In addition, effective cooperation between States, the IAEA and other stakeholders can facilitate a more cost effective and efficient implementation of safeguards that also minimizes the impact on nuclear facility operations. To this end, this guidance is intended to increase understanding of the safeguards obligations of both the State and the IAEA and, as a result, improve safeguards implementation at a reduced cost to all parties.

The IAEA gratefully acknowledges the assistance received through the Member State Support Programmes to IAEA safeguards from Argentina, Belgium, Brazil, Canada, China, Finland, France, Germany, Japan, the Republic of Korea, the United Kingdom, the United States of America and the European Commission in the preparation of this report. The safeguards related information in this publication has been reviewed by the IAEA Department of Safeguards. The technical officers responsible for this report were J. Sprinkle of the Division of Concepts and Planning and D. Kovacic and M. Van Sickle of the Division of Nuclear Power.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The IAEA works to enhance the contribution of nuclear energy to peace and prosperity around the world, while helping to ensure that nuclear material is not diverted to be used in nuclear weapons or other explosive devices. This publication is part of an IAEA guidance series developed to assist facility designers and operators in the consideration of international nuclear material safeguards. International safeguards provide for independent verification by the IAEA that States are complying with their obligations in relation to nuclear material and activities. It is widely recognized that establishing and maintaining effective national controls on nuclear material and activities is not only a legal obligation under the Treaty on the Non-Proliferation of Nuclear Weapons, but is also in the national interest of each State. Nuclear material is one of the more expensive assets in a nuclear facility and accounting for and keeping control of expensive assets is a recognized business practice. A State lacking control of nuclear material and activities risks becoming the target of actors involved in the proliferation of weapons technology or in clandestine nuclear related activities, as well as risking suffering financial losses owing to a loss of nuclear material.

This guidance is applicable to the design and construction of nuclear power reactors, such as the one shown in Fig. 1, as well as to research reactors. It complements the general considerations addressed in International Safeguards in Nuclear Facility Design and Construction [1] and is written primarily for nuclear reactor designers and operators. This guidance is written at an introductory level for an audience unfamiliar with international safeguards and has no legal status. Any State may incorporate elements of this guidance into its regulatory framework, as it deems appropriate. For official guidance on international safeguards implementation, the reader can refer to IAEA information circulars (INFCIRCs) available from the IAEA web site and they can contact the relevant safeguards authorities at the IAEA or in the State.

FIG. 1. Obrigheim Nuclear Power Plant, Germany (photograph courtesy of Siemens AG).

Safeguards by design (SBD) is defined as the process of including international safeguards considerations throughout all phases of a nuclear facility life cycle; from the initial conceptual design to facility construction and into operations, including design modifications and decommissioning. Good systems engineering practice requires the inclusion of all relevant requirements early in the design process to optimize the system to perform effectively at the lowest cost and minimum risk [2]. SBD has two main objectives: (1) to avoid costly and time consuming retrofits or redesigns of new nuclear facilities to accommodate safeguards and (2) to make the implementation of international safeguards more effective and efficient at such facilities for the operator, the State and the IAEA [3, 4]. SBD seeks to reduce the impact of safeguards on the design and construction cost and schedule, to mitigate the potential for negative impact on facility licensing (e.g. if retrofits are required for international safeguards purposes after successful licensing action, will those retrofits affect the licence?) and to help build public confidence.

Safeguards should be considered early in the design so that potential accommodations can be better integrated with other design considerations such as those for operations, safety and security. In the IAEA publication Governmental, Legal and Regulatory Framework for Safety [5], Requirement 12 (Interfaces of safety with nuclear security and with the State system of accounting for, and control of, nuclear material) states:

> "The government shall ensure that, within the governmental and legal framework, adequate infrastructural arrangements are established for interfaces of safety with arrangements for nuclear security and with the State system of accounting for and control of nuclear material."

Considerations of safety, security and safeguards are essential elements of the design, construction, commissioning, operation and decommissioning stages of nuclear power plants, as discussed in the IAEA Nuclear Security and IAEA Nuclear Safety publication series. The trend is for new plants to be built with inherent safety and security features as well as accommodations for safeguards as expressed in the Nuclear Power Plant Exporters' Principles of Conduct [6]. A new publication, Safety of Nuclear Power Plants: Design [7], contains a requirement, Requirement 8 (Interfaces of safety with security and safeguards), which states that:

> "Safety measures, nuclear security measures and arrangements for the State system of accounting for, and control of, nuclear material for a nuclear power plant shall be designed and implemented in an integrated manner so that they do not compromise one another."

The implementation of SBD is at its core a dialogue, not a set of specifications. SBD is not a new legal requirement. It is a voluntary process to facilitate the improved implementation of existing safeguards requirements[1] (GOV/2554/Att.2/Rev.2 and INFCIRC/153 are discussed in Ref. [8]), providing an opportunity for stakeholders to work together to build international confidence and to reduce the potential of unforeseen impacts on nuclear facility operators during the construction, startup and operation of new facilities. SBD should not be confused with good safeguards design alone, but rather it enhances design by early inclusion of safeguards in the facility project management. As such, cooperation on safeguards implementation is improved when (a) the designer, vendor and operator understand the basics of safeguards and (b) the safeguards experts understand the basics of the facility operations.

Safeguards implementation is always evolving; in particular, the intensity with which safeguards measures are applied can vary. One might reasonably expect more change in the frequency and duration of inspections than changes in the activities during inspections. From a design perspective, there is value in understanding the full range of potential safeguards activities and their impact on the facility design before design choices are fixed. In addition, early planning can incorporate flexibility into the facility's safeguards infrastructure, facilitating safeguards innovations. This flexibility will chiefly benefit the owner and operator of the nuclear reactor after the design process is complete, so it is in their interest to be an active participant in this process as early as is feasible.

Safeguards may be a little known area for some designers and vendors. However, they might have an interest in SBD because a design that facilitates the incorporation of international safeguards requirements is likely to be more appealing to a customer in a State where safeguards are obligatory. Meanwhile, the operator is ultimately responsible for IAEA safeguards implementation within the facility and having a facility that includes features facilitating safeguards requirements can potentially make safeguards cost less and have reduced impact on operations at that facility (e.g. the potential for fewer inspection days for physical inventory taking and verification). Depending on the project need, the SBD effort can range from better implementation of a known safeguards approach to a diversion pathway assessment.

Historically, safeguards have been retrofitted into existing facilities and safeguards requirements have been applied late in the design–build–operation process, thus possibly leading to a perception that safeguards are beyond the scope of the facility design team. However, when safeguards requirements are addressed early in a project, the IAEA estimates that the implementation cost can be as small as 0.1% of the capital cost of a nuclear power plant. Without adequate planning and preparation, not only can the cost be significantly more, but the disruption to the

[1] Note that, in States with a comprehensive safeguards agreement in force, preliminary design information for new nuclear facilities and activities, and for any modifications to existing facilities, must be submitted to the Agency as soon as the decision to construct or to authorize construction, or to modify, has been taken.

construction and licensing process can also be significant. Involving the design–build–operation teams in the SBD process carries the potential benefits of:

— Increasing awareness of safeguards for all stakeholders;
— Reducing inefficiencies in the IAEA's safeguards activities;
— Improving safeguards implementation;
— Facilitating the consideration of joint use of equipment by the operator and inspectorate[2];
— Reducing operator burden for safeguards;
— Reducing the need to retrofit for installation of equipment;
— Increasing flexibility for future equipment installation.

1.2. OBJECTIVE

This publication is part of a series being prepared to help inform designers, governments and the public about nuclear material safeguards. It provides information regarding the implementation of international safeguards that States, operators or other entities may take into consideration when planning new nuclear facilities. Proper implementation during construction will facilitate the safeguards activities required during the subsequent facility operation and decommissioning. This publication includes experience gained in past efforts to incorporate safeguards requirements in the facility design which can be useful in future efforts to build or operate nuclear facilities.

1.3. SCOPE

This publication was written to support the consideration of safeguards in the design of nuclear reactors. It is primarily for reactor designers and operators, although vendors, regulators and other stakeholders may also benefit from the guidance provided. It is directed at the baseline case of light water reactor (LWR) facilities; however, additional reactor types and variations are discussed in Section 5. The scope encompasses fresh fuel receipts at the reactor site and the on-site storage of irradiated fuel.

1.4. OTHER SAFEGUARDS RELATED RESOURCES

Other reference material can help provide States and interested stakeholders with an overview and background information on international safeguards. The IAEA web site has links to:

— Guidance for States Implementing Safeguards Agreements and Additional Protocols [8];
— The Safeguards Glossary [9];
— The Safeguards System of the International Atomic Energy Agency [10];
— Other material of general interest.

Additional resources are suggested in the Bibliography at the end of this publication.

1.5. STRUCTURE

Section 2 has a brief introduction to IAEA safeguards while Section 3 describes an approach for stakeholder interactions and integrating the consideration of safeguards into the design and construction process. Section 4 contains guidance for LWRs, much of which is applicable to all reactors. Section 5 contains additional guidance for other reactor types.

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[2] In this publication, inspectorate includes the IAEA, State and regional safeguards authorities.

Annex I contains specialized terminology used by the international safeguards community [9]. Annex II summarizes the information in a design information questionnaire. Annex III summarizes a questionnaire to assess the safeguardability of a nuclear facility design. Annex IV presents a matrix of safeguards considerations that is available from the Division of Concepts and Planning in the IAEA Department of Safeguards as a Microsoft Excel file.

2. OVERVIEW OF IAEA SAFEGUARDS

A basic understanding of IAEA objectives and activities can facilitate the consideration of international safeguards in nuclear facility design and construction. This section provides a brief overview of IAEA safeguards; more detailed information is available in Refs [8–11] and on the IAEA web site.

2.1. IAEA SAFEGUARDS

Pursuant to the IAEA's authority to apply safeguards stemming from Article III.A.5 of its Statute, the IAEA concludes agreements with States and with regional safeguards authorities for the application of safeguards. These agreements are of three main types: (1) comprehensive safeguards agreements (CSAs), (2) item specific safeguards agreements and (3) voluntary offer agreements. A State with any one of these agreements may also conclude a protocol[3] additional to its safeguards agreement [8]. Most safeguards agreements in force are CSAs and this publication focuses on those. A CSA requires safeguards to be applied to all nuclear material in all facilities and other locations in a State.

Safeguards implementation continually evolves to address new challenges, to incorporate lessons learned and to take advantage of new technologies and techniques. Since the early 1990s, safeguards has evolved to take advantage of increased information available to the IAEA about a State's nuclear program and related activities. Where the IAEA used to implement more or less identical safeguards approaches at facilities of the same type, now safeguards are customized for an individual State based on its fuel cycle and other factors.

To ensure an overall non-discriminatory approach to all States, the following three State level safeguards objectives apply to all States with a CSA:

- To detect undeclared nuclear material or activities in the State as a whole;
- To detect undeclared production or processing of nuclear material in declared facilities or locations outside facilities;
- To detect diversion of declared nuclear material in declared facilities or locations outside facilities.

To achieve these State level objectives, underlying technical objectives are established for each State. These technical objectives are based on a comprehensive analysis of how a particular State could divert, produce and/or import nuclear material for a nuclear weapon. Such technical objectives may differ between States, depending on their nuclear activities, capabilities or other State specific factors. Safeguards measures to achieve these technical objectives are identified. The acquisition path analysis, technical objectives and safeguards measures to achieve these objectives are documented in a State level approach for each State with a CSA. While nuclear material accountancy at nuclear facilities remains fundamental, the use of other information relevant to safeguards means that safeguards at similar facility types may differ from State to State, as well as from facility to facility within the same State. Therefore, no single specification exists for safeguards implementation.

[3] INFCIRC/540 (Corrected), Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency for the Application of Safeguards.

2.2. SAFEGUARDS MEASURES

The intensity of safeguards measures chosen by the IAEA will evolve over time, and will be adjusted and maintained by the IAEA Department of Safeguards. In general terms, the safeguards activities performed will verify the State's declarations about nuclear material quantities, locations and movements at that facility.

Safeguards techniques and measures used by the IAEA can include:

- On-site inspections by IAEA inspectors [12];
- Material balance areas (MBAs) for nuclear material accounting [11];
- Key measurement points for measuring flow and inventories of nuclear material [11];
- Unique identifiers for nuclear material items;
- Locations for surveillance, containment and monitoring and other verification measures;
- Nuclear material measurements [11, 13, 14];
- Review of operating records and State reports;
- Annual physical inventory verification (PIV), generally performed during facility shutdown;
- Routine interim inventory verifications (monthly, quarterly, annual or random);
- Verification of transfers of nuclear material to and from the site;
- Statistical assessment of the nuclear material balance to evaluate material unaccounted for;
- Reactor power monitoring;
- Verification of facility design for features relevant to safeguards;
- Verification of the performance of the operator's measurement system.

These activities are not of equal importance. Additional information can be found in the most recent edition of IAEA Safeguards Techniques and Equipment, currently Ref. [14].

Additional activities have been found useful to detect and deter undeclared nuclear material or activities. For example, the IAEA can use short notice random and unannounced inspections[4] to optimize resource allocation while maintaining safeguards effectiveness. It also uses unattended monitoring to verify activities that occur when the inspector is not present on-site. In addition, 117 States[5] with CSAs have brought an additional protocol into force, which defines activities — in addition to those implemented under their safeguards agreement — useful for verifying the completeness of the State's declarations to the IAEA. *Familiarity with the processes, layout, equipment and other characteristics of a given nuclear facility is essential for developing and maintaining an optimal safeguards approach, and the designer can facilitate IAEA familiarization activities.*

It is important for the IAEA to verify these features relevant to safeguards before taking them into account. The IAEA can use facility design information to:

- Select strategic points for determining nuclear material flows and inventory.
- Select measurement points and methods.
- Select surveillance, containment and monitoring locations and methods.
- Establish recording and reporting requirements.
- Develop a design information verification plan.
- Establish a site specific list of items (equipment, systems and structures) essential for the declared operation of the facility (a safeguards essential equipment list).
- Assess whether the facility is being used to full capacity.
- Provisional design information can be provided to the IAEA before a decision takes place to construct a nuclear facility and can be revised as the design becomes more detailed [1, 8].

One can specify when the information is provided which information is conceptual, which is preliminary, and which is understood to be fixed. Annex II lists a summary of the type of information provided to the IAEA in a design information questionnaire (DIQ).

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[4] Short notice random and unannounced inspections are explained in Annex 1: Terminology.

[5] As of 22 November 2013.

For nuclear material accountancy, one or more nuclear MBAs will be established. By definition, an MBA is an area where (a) the quantity of nuclear material in each transfer into or out of the MBA can be determined and (b) the physical inventory of nuclear material can be determined. The operator's and the IAEA's MBA boundaries do not have to be identical; however, the verification activities might be simpler if they are. The nuclear material in an MBA is characterized as either direct use material (i.e. nuclear material that can be used for the manufacture of nuclear explosive devices without further transmutation or enrichment), or indirect use material (i.e. all other nuclear material), or a combination of both. IAEA verification activities are typically more intensive for direct use material.

The IAEA distinguishes between 'item' and 'bulk handing' facilities. In 'item' facilities, the nuclear material is contained in discrete items (not designed to be opened) such as fuel rods or fuel assemblies in a typical LWR. In 'bulk handling' facilities, the nuclear material is handled in loose form and can be repackaged with the possibility of combining or splitting up the quantity of nuclear material in containers, and also of changing the chemical or physical form of the nuclear material. Different safeguards measures are applicable to the verification of items and bulk materials. IAEA verification activities at bulk facilities are generally more intensive [11].

2.3. DIVERSION, MISUSE AND UNDECLARED ACTIVITIES

In an acquisition path analysis, the IAEA considers all potential means that a State can use to acquire unirradiated direct use nuclear material to subsequently manufacture a nuclear explosive device. This analysis takes the existing nuclear capabilities of the State into account and how these capabilities can be complemented, misused or diverted to enable the production of weapons useable material. The analysis will assume the possibility of undeclared nuclear material and activities. Other relevant information about a State is also analysed and safeguards measures are implemented to detect the diversion of declared nuclear material and undeclared activities.

The IAEA considers two types of diversion: abrupt and protracted. In an abrupt diversion scenario, the IAEA assumes that a large quantity of nuclear material is removed in one batch from one location. In a protracted diversion, the removal occurs over a long period, perhaps more than a year, and can be a continuous flow, intermittent or even taken from different locations.

2.4. VERIFICATION

IAEA verification activities at a facility fall into two broad categories — verification of design information and verification of the accountancy system. Figure 2 shows inspectors becoming familiar with a facility as part of a design verification exercise.

FIG. 2. IAEA design verification.

Updated facility design information is to be provided for any changes relevant to safeguards in operating conditions throughout the facility life cycle. The IAEA verifies this information through on-site physical examination of the facility during the construction and subsequent phases of the facility's life cycle. During a typical early design information verification at a reactor, IAEA inspectors can be on-site to inspect and photograph the concrete forms prior to the concrete pour. In later design information verifications, they can walk through the facility with detailed building plans to confirm the as-built design and to look for design features not shown on the drawings. The IAEA can also verify the design and capacity of any processing equipment and systems in the reactor facility. As part of this design and capacity assessment, it is important for the IAEA to verify the maximum capacity of the plant, which includes verifying the limitations on possible misuse. In addition, the IAEA will develop an 'essential equipment' list for the nuclear facility to help monitor whether the facility is in an 'unable to operate' status. The designers of the facility can play a valuable role helping to identify the equipment essential for operating the nuclear facility.[6]

One of the main purposes in the verification of nuclear material accountancy [11] is to evaluate the facility's records in order to detect any diversion of nuclear material from declared activities. One activity undertaken by the IAEA is the annual PIV during which the physical contents of the facility (consisting of the actual nuclear material items) are compared with the nuclear material accounting records. Figure 3 illustrates a PIV exercise in a reactor's fresh fuel storage area.

FIG. 3. PIV exercise in fresh fuel store.

Verification of nuclear material accountancy can include assessment of the operator's measurement systems including their measurement uncertainties. Given resource limitations and the need to minimize impeding facility operations, statistical sampling is often used in the verification of a facility measurement system. Items are selected at random and verified by a number of measurement methods. These methods can include item counting or either qualitative or quantitative measurements. The IAEA makes use of several categories of measurements. Three of general interest to designers are measurements that detect gross, partial or bias defects in the declared quantity of nuclear material [9].

— Gross defect refers to an item or batch that has been falsified to the maximum extent possible, so that all or most of the declared material is missing.
— Partial defect refers to an item or batch that has been falsified to such an extent that some fraction of the declared amount of material is actually present.
— Bias defect refers to an item or batch that has been slightly falsified so that only a small fraction of the declared material is missing.

[6] The IAEA *safeguards* essential equipment list is different from the *safety* essential equipment list.

The IAEA can perform gross defect measurements on fresh or irradiated fuel at a reactor. It can perform item counting and identification checks, or it can apply gross defect measurements to irradiated fuel when it is transferred. Figure 4 shows verification measurements of fresh fuel in their shipping containers at the reactor.

FIG. 4. Verification of fresh fuel transport containers using a hand-held HM-5 gamma monitor [14].

Figure 5 shows measurements of irradiated fuel (irradiated direct use material) in the reactor spent fuel storage pond. For an item facility such as a reactor, differences between the physical inventory and the accounting records are generally investigated by means other than statistical evaluation of measurement errors, e.g. by investigating the completeness and correctness of facility records. Provision can be made in the design and in operations to facilitate the controlling and verifying of the quantities, locations and movements of the nuclear material.

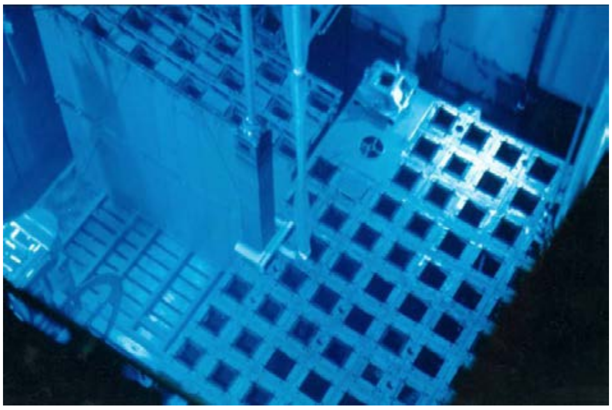

FIG. 5. An irradiated fuel measurement in a spent fuel pond [14].

Surveillance, containment and monitoring measures supplement the nuclear material accountancy measures by providing means to detect undeclared access to, or movement of, nuclear material or safeguards equipment. Containment refers to the structural components that make undetected access difficult. Seals are tamper indicating devices used to secure penetrations in containment thereby preventing undetected access. Surveillance is the collection of optical or radiation information through human and instrument observation/monitoring. During inspections, inspectors can examine the surveillance, containment and monitoring systems, including relevant facility design features, as part of verifying operator records and systems. The IAEA has several surveillance systems approved for use [14] that:

— Store data;
— Include local battery backup;
— Provide state of health or picture data to an off-site location;
— Can be triggered by other sensors;
— Are sealed in tamper indicating enclosures.

Figure 6 shows the interior of a tamper proof surveillance system and a typical installation. Facility provision of adequate illumination is necessary to facilitate the IAEA's surveillance activities.

FIG. 6. Next generation IAEA surveillance system [14].

Maintaining 'continuity of knowledge' refers to the process of using surveillance, containment and monitoring measures to maintain already verified safeguards information by detecting any efforts to alter an item's properties which are relevant to safeguards. When continuity of knowledge is maintained successfully, it can reduce the amount of remeasurement activity in subsequent inspections. Figure 7 shows an inspector using seals to maintain the continuity of knowledge during a routine inspection.

FIG. 7. Use of seals to maintain continuity of knowledge.

As the number of fuel cycle facilities and the amount of nuclear material under safeguards expands, the IAEA is challenged to develop more efficient ways to implement effective safeguards. The use of unattended monitoring systems allows inspectors to focus more effort on doing what humans do best, e.g. investigating possible undeclared activities, detecting irregularities in operations or noticing items out of place. Furthermore, the remote transmission of safeguards data from unattended monitoring systems can notify the IAEA when equipment needs maintenance, provide information to help plan inspections and reduce IAEA time on-site conducting inspections, thereby reducing the impact of inspections on facility operation in addition to making safeguards implementation more effective and more efficient.

2.5. FACILITY PHYSICAL INFRASTRUCTURE REQUIREMENTS FOR IAEA SAFEGUARDS ACTIVITIES

The basic requirements of IAEA safeguards equipment include physical space, uninterruptible power and a data transmission backbone. Figure 8 illustrates a surveillance camera being installed which requires dedicated physical space, electrical power and data archive capability. Even without detailed IAEA design criteria for safeguards equipment or systems, which might be specified only late in the design life cycle, provision of cabling and penetrations can be included in the design. The ability to provide access to stable, reliable power and access to secure data transmission capability throughout a nuclear facility would address some of the most costly aspects of retrofitting for safeguards equipment systems and allow flexibility for future safeguards technology installation.

FIG. 8. Installation of a surveillance system.

Safeguards technologies continue to evolve, as does nuclear technology. An ability to easily upgrade systems is dependent on the flexibility of the facility infrastructure design. Figure 9 illustrates that support electronics for IAEA measurement hardware are changing, often in the direction of reduced physical size and increased capability, as technology evolves. A facility design that accommodates modest changes in equipment size, shape and power requirements allows the use of newer alternatives as they become available on the market or as obsolescence removes older alternatives. Reference 8 includes information about the functions, size and infrastructure requirements of IAEA equipment.

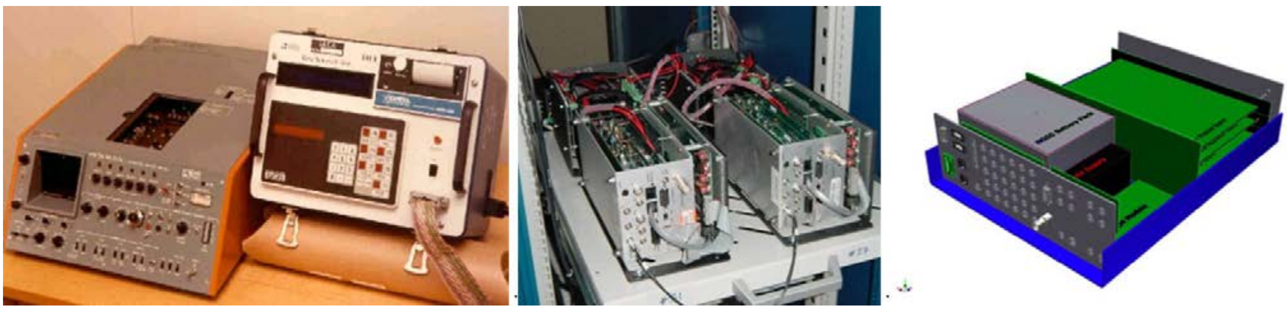

FIG. 9. The packaging of gamma ray measurement support electronics is evolving (left: 1987; middle: 2000; right: 2013).

3. STAKEHOLDER INTERACTION

The IAEA recommends early stakeholder interaction, which is vital for the effective implementation of safeguards. In addition to the IAEA, other stakeholders are designers, vendors, project managers, operators and safeguards authorities.

3.1. STAKEHOLDERS

3.1.1. Designers and vendors

Designers and vendors have the responsibility for understanding the many requirements relating to safeguards, security and safety as well as operational requirements. These requirements can include detailed information about safeguards activities, e.g. those that require access, instrumentation that must be installed or any physical infrastructure in the facility necessary to support safeguards equipment. Safeguards expertise should be included in the design team.

3.1.2. Project manager

The project management has the responsibility for managing the competing interests, bringing the design/construction project to a successful conclusion and, ultimately, delivering a quality facility ready to operate. The use of a safeguards project dossier, where relevant documentation can be kept in a single place shared by all stakeholders, can be useful to maintain critical knowledge as the project evolves. Significant differences can exist between the original design, the as-built drawings and the as-is operating configuration. A dossier is particularly useful given the extended timescales of nuclear projects, which mean that staff turnover can be expected. It is recommended that project managers understand enough about safeguards to make informed decisions regarding safeguards impacts.

3.1.3. Operators

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

3.1.4. State or regional safeguards authority

The safeguards authority has the responsibility for fulfilling the obligations of the State as defined by treaties and agreements, including formal communications with the IAEA [8]. The authority responsible for safeguards implementation in the State may involve more than one entity in the government, a regional entity, or a combination. In some States, the authority for safeguards does include the regulatory authority. Additional communication between stakeholders such as designers, vendors, operators and the IAEA can be arranged and encouraged by the safeguards authority.

3.2. SAFEGUARDS CONCERNS AT STAGES OF DESIGN

Each phase in the life cycle of the facility can benefit from consideration of safeguards. While safeguards implementation potentially has a small impact on project cost and schedule when considered early in the design process, failure to do so can result in a much larger impact than necessary, both in construction and during operation. Figure 10 depicts the stages of design in a simplified form, and potential SBD implementation at each stage is discussed below. The safeguards authority is the official contact with the IAEA and should be included in the safeguards dialogue as a stakeholder or as an observer, as appropriate. When the designer and the operator are from different States, each may report to a different safeguards authority. Once a location in a State is selected for the nuclear facility, the corresponding safeguards authority will be the official contact with the IAEA.

FIG. 10. Facility design stages.

Conceptual design — the project planning period, the earliest design stage where preliminary concepts for safeguards measures might be discussed.

— A designer/operator can work with the safeguards authority to ensure that the IAEA is aware of the design and can begin engagement.
— The IAEA might perform an evaluation of the operational process for features relevant to safeguards and to propose possible safeguards measures for consideration.
— The IAEA suggests preliminary considerations for a safeguards approach and negotiations begin.
— The designer, the operator and the IAEA can identify and mitigate potential safeguards risks in the conceptual design.

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

— The IAEA can make a preliminary definition of MBAs and key measurement points.
— All can consider how the design can be optimized to meet both operational and safeguards goals.
— The designer can assess whether the design supports the physical infrastructure necessary for safeguards instrumentation and equipment.
— An analysis[7] can be performed to verify that no unmonitored opportunities for diversion or misuse exist.

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

— Stakeholders review detailed facility design.
— Stakeholders confirm safeguards equipment can meet requirements.
— Preparation of DIQ.

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

— Conducts design verification activities;
— Reviews and records as-built status;
— Monitors installations relevant to safeguards;
— Confirms that safeguards equipment meets requirements.[8]

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

[8] During construction, safeguards equipment can be confirmed to be functional without nuclear material in the facility, whereas operational status includes all necessary aspects for routine operation (e.g. calibration, positioning and certification), including operation of the equipment with nuclear materials present.

Operation — the operator starts up the facility[9] and systems testing begins. The IAEA confirms that:

— As-built documentation exists for design information verification and safeguards equipment.
— As-is documentation relevant to safeguards is correct.
— The safeguards equipment meets requirements and is operational.
— Safeguards equipment can be commissioned before nuclear material is introduced to test the facility operations.
— The first nuclear material introduced to a new facility is used to calibrate or test the safeguards equipment.

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

— Conducts design verification activities;
— Verifies the removal of nuclear material;
— Confirms the removal or disabling of essential equipment;
— Terminates safeguards on the facility.

3.3. PROJECT LIFE CYCLE COST EVOLUTION

Large projects involving both design and construction can be expected to address a wide variety of regulatory and operational requirements and also to resolve conflicts between requirements with minimal additional cost to the project. In general, large projects endeavour to resolve conflicts early — to reduce retrofits and to eliminate shortcomings (or design defects) from the design early in the project — in order to minimize the negative impacts of change on both cost and schedule. Systems engineering has documented that the impact and cost of changes before design features are finalized is smaller than when they are changed after the design is finalized [15]. Costs for design and construction might be as much as 70% committed at the conclusion of the conceptual design phase of the project. Figure 11 displays a hypothetical example of the cumulative project costs as a function of time, where it is assumed the conceptual design is 8% of the total cost, the design is 7% of the cost, development and testing is 35%, and the operation through disposal is 50% of the total project cost. Overlaid on the figure is the cost to address design changes — the cost to remove defective design features — which is shown to increase by orders of magnitude when adjustments are made late in the process rather than early. While the exact values may vary, the figure illustrates the wide range of experience managing large projects of all types that early consideration of all requirements can reduce total project costs compared to delayed or incomplete consideration early in a project. Furthermore, the figure suggests that the costs of introducing changes once the facility is operating can be expected to be even higher than those incurred from changes late in the construction process. SBD recommends that the potential for cost escalations be included in considerations about when and how to address safeguards requirements.

4. SAFEGUARDS CONSIDERATIONS RELATED TO REACTOR DESIGN

The term safeguardability has been used to describe the ease of applying safeguards to a facility (Annex III [3]). A reactor facility can be designed such that nuclear material can be controlled and accounted for and the IAEA can independently verify the declarations made about that nuclear material with minimal cost impact. Perhaps the biggest benefit can come from including the infrastructure for the safeguards equipment in the design and construction, especially when penetrations are necessary for cabling. The importance of keeping as-built or as-is design documentation up to date cannot be overemphasized.

[9] The safeguards equipment should be certified for use before nuclear material is introduced into the facility.

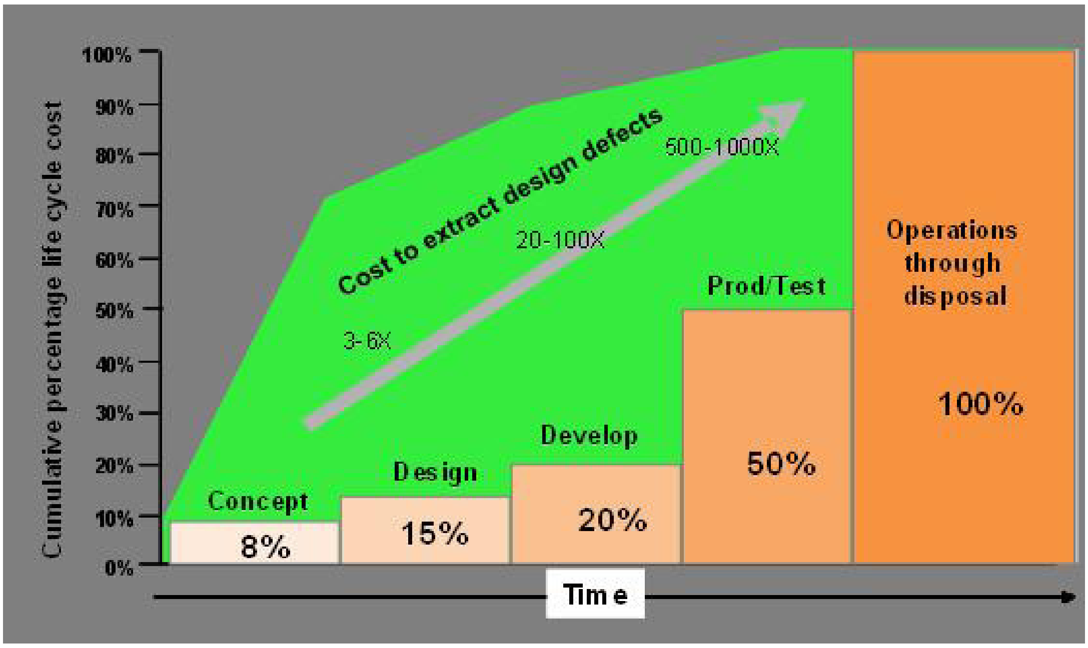

FIG. 11. Cumulative life cycle costs as function of time [15].

In this publication, the term ‘equipment list’ will be used in a generic way to represent various lists of equipment. This section uses a large LWR fuelled with low enriched uranium (LEU) as a baseline example. References [12, 16] provide additional information. Much of the baseline guidance can apply to any reactor type, and additional points addressing reactor variations are discussed in Section 5. Annex IV arranges the guidance in a table.

In the facility conceptual design stage, international safeguards can be considered using general guidance that is not overly prescriptive. Guidance that describes the safeguards issues, rather than prescribing how to address them, may be more useful to facility designers and operators at this stage. Dictating specific technology solutions for facility safeguards can be challenging since variability in facility designs and State specific factors preclude ‘one size fits all’ solutions. However, communication can usefully include descriptions of metrics for accuracy, precision and validation of results.

For example, while it is not feasible to identify an exact camera location until the design of the parts of the facility to be under surveillance is fixed, it is feasible to inform the designer that a camera needs adequate illumination, and which activities relevant to safeguards will require the placement and use of cameras. The designer can also include surveillance requirements as the layout and design are optimized. Specifications for the supply of electrical power, space and communications cabling can be discussed without knowing the exact location or height above the working level(s) of the final installation.

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

— How to facilitate inspection activities;
— How to minimize the need for IAEA inspectors to revisit the site for clarification of information collected during previous visits;
— How to mitigate safeguards issues during off normal (unusual) events;
— Where to install backup or emergency power and for how long this needs to be available.

Measures that can facilitate inspection activities include:

— Providing access to and space for safeguards equipment maintenance[10];
— Minimizing radiation exposure of inspectors (and equipment);
— Providing access to and space for design verification (e.g. containment and piping);
— Minimizing the potential for damage to safeguards equipment or loss of safeguards data;
— Providing adequate illumination for personnel access and for surveillance;
— Clearly labelling safeguards equipment and its physical infrastructure in English and in the facility operator's native language;
— Providing unique identifiers for each nuclear material item;
— Suggesting reliable, low maintenance options for equipment.

The greatest technical challenge for safeguarding a reactor concerns direct use material. Any unirradiated[11] HEU, ^{233}U or plutonium (including mixed oxides) will have the most stringent verification requirements including measurement frequency and sensitivity. Misuse of a reactor to produce irradiated direct use material can be difficult to detect. Also of interest is whether the facility has fuel pin replacement capability, since the ability to disassemble a fuel assembly to remove or replace a pin breaches the item accounting integrity of the fuel assembly. Low enriched uranium fresh fuel will have less frequent verification and measurement sensitivity requirements.

In a reactor facility, the nuclear material comes into the reactor as fresh fuel, is used in the core to provide energy (fuel can be shuffled in the core to flatten the power distribution and to optimize fuel burnup), moved to wet storage at the reactor, and then moved to dry storage near the reactor or shipped to wet or dry storage facilities away from the reactor site. While the core is operating, the nuclear material inside the core is fissioned and/or transmuted and plutonium or ^{233}U may be produced in large quantities. It is not easy to calculate the new isotopic or spatial distributions of the nuclear material in the irradiated fuel accurately, and it is even more difficult to measure these characteristics accurately.

Inventory key measurement points are generally located in the fuel storage areas: fresh fuel storage, reactor core and reactor spent fuel storage. Flow key measurement points are located at fuel transfer sites: fresh fuel receipts, fuel transfers from fresh fuel storage to the reactor core, irradiated fuel transfer from the reactor core to spent fuel, transfer of recirculating core fuel, transfer of spent fuel to storage and spent fuel transfer/shipment from the MBA/facility.

Figure 12 depicts a simplified MBA and key measurement point layout for an LWR, including four flow key measurement points (labelled 1, 2, 3, 4) and three inventory key measurement points (labelled A, B, C). The dark line indicates the facility boundary, with key measurement point 1 and key measurement point 4 assigned to measure items that cross the facility boundary.

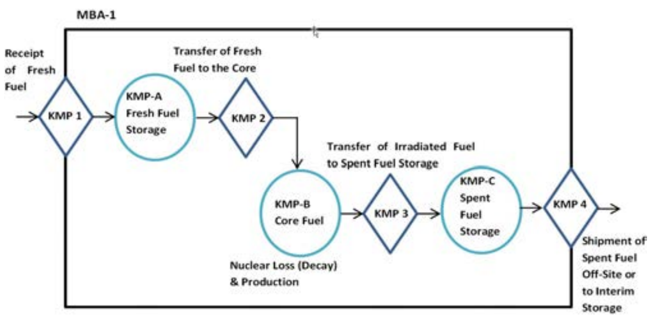

FIG. 12. Material balance area and key measurement points for an LWR.

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

[11] For safeguards purposes, unirradiated implies the lack of fission products, not whether the nuclear material itself has been irradiated.

The safeguards approach at a power reactor includes surveillance, containment and monitoring measures. Possible safeguards approaches to surveillance, containment and monitoring are shown in Figs 13 and 14. Figure 13 depicts a reactor design with its associated spent fuel pond located inside the reactor containment and Fig. 14 depicts a reactor design with the spent fuel pond located outside the reactor containment. In these illustrations of surveillance, containment and monitoring equipment, surveillance cameras and tamper indicating seals are positioned to view areas or activities of potential safeguards interest, some within the containment.

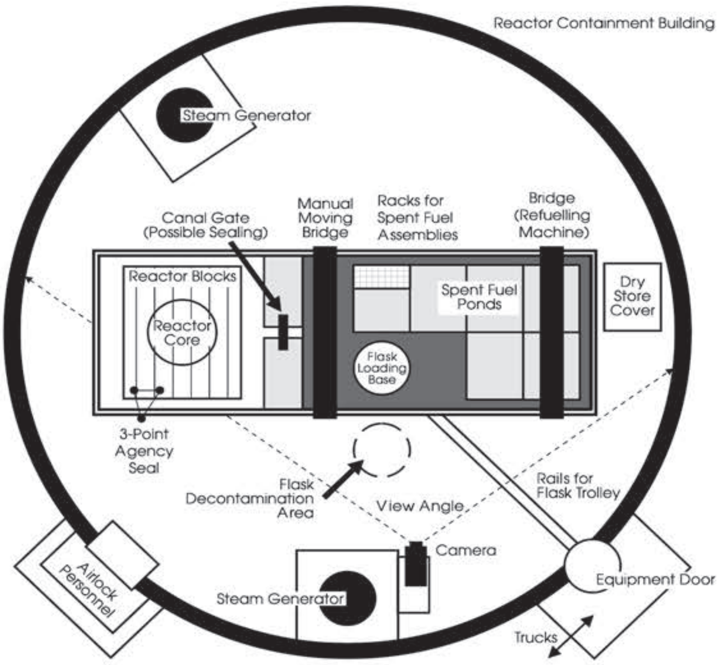

FIG. 13. Typical safeguards surveillance, containment and monitoring equipment for a reactor with spent fuel stored inside containment.

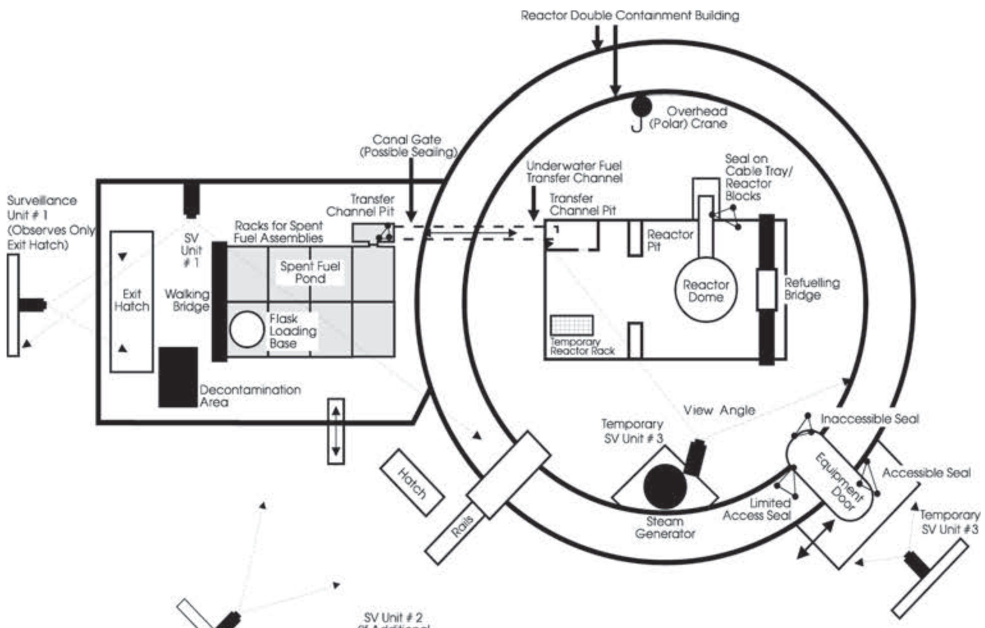

FIG. 14. Typical safeguards surveillance, containment and monitoring equipment for a reactor with separate spent fuel storage (SV=surveillance).

Safeguards equipment at reactor facilities can include:

- — Cameras in the reactor hall, above the fuel ponds and monitoring core activities;
- — Seals on containment penetrations and important fuel transfer channels;
- — NDA measurements of fresh and irradiated fuel.

Actual locations and the numbers of units and seals are determined for each facility according to the specific design. A designer can potentially consider the safeguards surveillance, containment and monitoring needs and also any measurement equipment needs as part of the design optimization process. Figure 14 depicts the use of additional temporary cameras during reactor refuelling or maintenance operations. In addition, these figures illustrate some of the difficulties inspectors can encounter when trying to monitor multiple activities or areas with a single surveillance camera. In some facilities, multiple cameras are required as a consequence of how the internal components are arranged. Consideration of safeguards early in the design layout may help mitigate difficulties with the efficient application of surveillance, containment and monitoring.

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

4.1. MISUSE/DIVERSION SCENARIOS

‘Misuse/diversion’ refers to the misuse of the facility and/or the diversion of nuclear material. For existing reactor designs in current operation, the misuse/diversion scenarios have been addressed with the safeguards approach. Reconsideration of these designs by a design team is not expected to be cost effective. However, a basic understanding of current safeguards practice might be useful to them. For innovative designs, an analysis can be performed, possibly in collaboration with the State and/or regional safeguards authorities and the IAEA, to identify possible misuse and diversion scenarios. Annex III and Refs [17–19] discuss possible methods for analysis.

There are two basic misuse/diversion scenarios for nuclear reactors: (1) undeclared production and (2) diversion from the declared inventory. The misuse involves the production of undeclared nuclear material from undeclared irradiation targets in the reactor.

It might be helpful for designers to become familiar with the concept of diversion and misuse scenarios and the related pathways that safeguards are intended to address. Designers can consider all types of diversion, including abrupt and protracted diversion, and misuse followed by diversion. Some examples of possible misuse/diversion scenarios and potential safeguards measures to address the scenarios are described in Table 1 (and are also discussed on page 17 of Ref. [16]).

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

- — Minimal number of penetrations in the containment structure and/or pool building;
- — Design accommodations that minimize the required number of tamper indicating seals and that facilitate use of seals;
- — Layout of the facility and access to camera locations to minimize the need for multiple surveillance systems, including the preparation of camera mounting locations;
- — Features to easily distinguish fuel and non-fuel items;
- — Access controlled spaces for receipts, storage and measurement of nuclear items;
- — Easy to read, unique identifiers for nuclear material items.

TABLE 1. MISUSE/DIVERSION SCENARIOS

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

4.2. GENERAL GUIDANCE

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

- To provide infrastructure support (e.g. normal and backup power, lighting for surveillance, access, dedicated space, data transmission capability) inside the facility. Figure 15 shows the operator providing installation support during emplacement of IAEA equipment.
- If a video surveillance or fuel flow monitoring system is used that requires a data collection cabinet, to install the cabinet in an area/room protected from extreme temperature, humidity and dust.
- To minimize the number of access points in the reactor containment and other shielding structures through which any fresh or spent fuel movement can take place.
- To design for adequate uninterruptible electrical power to support safeguards equipment and instrumentation (e.g. instrument cabinet, instrument sensors, IAEA installed or facility illumination, cooling and heating) with battery/diesel generator/gas turbine backup for unattended systems.
- To plan the fuel transport routes so that surveillance, containment and monitoring and nuclear material flow monitoring systems have the ability to clearly distinguish between routine fuel transfers and other fuel activities, and also between fuel and non-fuel activities.
- To ensure that optical surveillance systems are not blocked by large pieces of equipment (e.g. the fuel handling crane).
- To consider penetrations through containment (e.g. the reactor safety containment) for cabling for safeguards equipment to avoid situations where penetrations have to be drilled in later during construction.
- To provide adequate access for attaching, replacing or servicing any seals.
- To minimize the effect of safeguards on plant operation by designing locations for safeguards equipment that are accessible for inspection, monitoring and maintenance and that do not obstruct or impede plant operations.

FIG. 15. Installation of IAEA equipment racks.

- — To ensure that inspectors can accomplish all safeguards activities safely and expeditiously and that safeguards equipment is reasonably protected from unintentional damage.
- — To consider provisions protecting proprietary and restricted information.
- — To clearly label all safeguards equipment (including cabling power supplies and switches) to avoid inadvertent interruptions in surveillance and monitoring.
- — To provide capabilities to enable the use of safeguards seals at key measurement points and features relevant to safeguards such as key junction boxes where cables are terminated or connected.
- — To ensure verification of spent fuel in storage without undue handling. Ease of verification can include unattended monitoring for fuel movement, surveillance, containment and monitoring of IAEA equipment inside of containment[12], and provisions for sealing of the storage to reduce the need to re-verify fuel assemblies and/or rods.
- — To provide a single dedicated space for safeguards' electronic equipment[13] that can be access controlled by the inspectorate. This space might include some additional room to accommodate future IAEA equipment.
- — To minimize the impact on facility operations from inspector's measurements by considering controlled space, access control and access to facility infrastructure (e.g. cranes, bridge over pool) for any required verification measurements.
- — To provide means to mitigate the consequences of losing safeguards continuity of knowledge from abnormal events.[14]

4.3. SPECIFIC LOCATIONS WITHIN A REACTOR

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

4.3.1. Shipping/receiving area

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

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

[13] Safeguards equipment generally has dedicated electronics racks for signal processing, batteries, and a data archive located remotely from the sensor; and in less hazardous space than the sensor location.

[14] For example, provide reliable backup power for occasions when a site loss of power might affect IAEA equipment.

the fresh fuel storage.[15] The activities relevant to safeguards that can be performed upon transfer to the fresh fuel storage include the following:

- The IAEA detaches the seal from the transport container.
- The operator unloads the transport containers and transfers the fresh fuel assemblies into the fresh fuel storage under IAEA observation.
- The IAEA identifies and counts each fuel item transferred into storage.

When spent fuel assemblies leave the nuclear facility, the activities relevant to safeguards to be performed vary from site to site. Usually, the transport cask is loaded in the spent fuel pond area, where inspectors will identify each fuel assembly and perform appropriate NDA measurements. Once the transport cask is full, it is closed and the inspector seals it, typically applying dual surveillance, containment and monitoring.[16] The transport container is then moved to the shipping area where it will stay under IAEA surveillance (usually provided by cameras) until shipment. The shipment itself does not necessarily require the presence of the inspector.

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

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

4.3.2. Fresh fuel storage

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

If the storage is in water, some NDA measurements require the placing of equipment in the water during the inspection. This aspect needs to be taken into account by the designer with due consideration of the facility's decontamination health and safety regulations and procedures.

From a safeguards point of view, it would be convenient to design the fresh fuel area and schedule operations in the area to minimize unnecessary access and activities. Minimization of off-site shipments and receipts can also be considered.

Design features for fresh fuel storage areas that assist in implementing safeguards include:

- Controlled access to the fresh fuel storage area, including a minimum number of access penetrations, with suitable arrangements to allow for sealing/surveillance;
- A layout of the fresh fuel storage that allows inspectors to verify and progressively seal groups of fuel assemblies as they are put into storage without affecting the continuity of knowledge of the fuel already in inventory;
- Adequate space and illumination between assemblies that allow inspectors to read the identifiers on fuel assemblies and conduct NDA measurements, specifically:
  - Provision for the use of the inspector's portable NDA equipment;
  - Arrangement of fuel within the storage area to minimize the need for moving fuel in order to identify specific assemblies.

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

[16] Dual surveillance, containment and monitoring refers to use of two surveillance, containment and monitoring measures for redundancy and reliability that do not share a common failure or tamper mode.

4.3.3. Spent fuel storage

LWR spent fuel is stored in spent fuel ponds to provide both cooling and biological shielding. Typical routine verification activities conducted during inspections include: item identification, measurements with a Cerenkov viewing device and/or gamma measurements [14]. Figure 16 shows an IAEA inspection using the reactor hall bridge crane with a Cerenkov viewing device to observe irradiated fuel. The area can be under optical surveillance, and the transfer channels between the core and the pond may be sealed.

FIG. 16. Verification of irradiated fuel using a Cerenkov instrument [14].

During routine inspections, surveillance data are reviewed on-site or collected for review and any seals are checked. Design considerations for spent fuel storage areas relevant to safeguards are:

— Some of the NDA measurements can require lowering equipment into the water during the inspection; this aspect can be considered in the design in coordination with health and safety issues.
— For one type of NDA measurement, the analysis of the Cerenkov glow emitted by each assembly in the pond might require the inspector to be able to position him/herself over each irradiated assembly, on a vertical axis to the assembly to be verified.
— Limiting access and activities in nuclear material storage or handling areas can facilitate IAEA review of surveillance, containment and monitoring data by reducing the number of events that are difficult to understand or interpret.

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

— A location that provides an unobstructed view of activities potentially involving nuclear material and that is suitable for the installation of surveillance equipment.
— Light sources in the room whose spectrum does not overlap with the characteristics of Cerenkov glow detection techniques.
— Storage racks, preferably configured in a single layer, that permit viewing directly from above the top of each fuel assembly with its identifier visible (e.g. no overhang over fuel storage locations which block the view).
— Provisions for verifying and sealing the fuel in the lower layer(s) if fuel storage is in more than one layer.
— An indexing system such that the inspectors can identify specific fuel assembly locations from the fuel handling control point.
— A minimum number of openings in the building structure through which it is possible to transfer spent fuel, with suitable arrangements to allow for their sealing/surveillance.

- Water clarity and surface stability that allow easy visual inspection of the fuel assemblies in their storage position and viewing of the Cerenkov glow from the assemblies. The Cerenkov glow requires water clarity in both the ultraviolet and visible light spectrums. Figure 17 is a close up view of inspectors using a Cerenkov viewing device directly above the spent fuel assembly.
- A spent fuel cooling water return route designed so as to prevent thermal turbulence near the surface of fuel assemblies.
- Provisions that facilitate the annual PIV that consists of counting the total number of spent fuel items and verifying spent fuel attributes by NDA measurement, specifically:
  - Minimizing the movement of fuel for counting and measurement purposes;
  - Providing adequate working space on the bridge for inspectors and equipment as illustrated in Figs 16 and 17 above;
  - For special cases (e.g. long cooled fuel, low burnup fuel or locations not vertically accessible), providing for the raising or quarantine of assemblies chosen for sampling to allow measurement using the inspector's equipment;
  - Providing a facility design for the fuel handling process and storage that facilitates the verification of fuel transfers out of the spent fuel pool (e.g. using remote monitoring);
  - Designing a location that facilitates safeguards during fuel reconstitution[17] such that, if possible, the flow of assemblies/rods into and out of the area follows predefined routes monitored by IAEA equipment.
- Provisions for inspection of any closed containers located within the spent fuel pool.
- Making it more difficult to hide an undeclared transfer cask.
- A hoist for a portable underwater camera used to item count and item identify irradiated fuel in the spent fuel pool or spent fuel cask.
- A minimum number of personnel access points into the area.
- Underwater storage locations for safeguards equipment used underwater.

FIG. 17. Inspector viewing irradiated fuel assemblies using a Cerenkov glow viewing device.

Interim spent fuel storage installations, which typically include a dry storage facility on the nuclear power plant site, can also benefit from SBD. Provision of design features to facilitate dual surveillance, containment and monitoring, item identification and access control are features relevant to safeguards that should be considered. Since such installations are increasingly implemented at nuclear power plants, they will be considered in the overall safeguards approach for a given reactor site. Industry may be aware of the relevant safeguards requirements and, where possible, accommodate them in facility designs.

[17] Some assemblies are designed to be capable of disassembly on-site in order to remove defective fuel pins and then reconstituted for re-use in the reactor, on-site.

4.3.4. Core

In off load refuelled reactors, which are refuelled while shut down, the core is usually sealed[18] for the entire irradiation (operating) period, and the core and/or core seals can be kept under optical surveillance. Prior to refuelling, the inspector might install a backup temporary surveillance camera to reduce the possibility of a loss of continuity of knowledge in case of a camera failure. When refuelling takes place, inspectors might be present and perform core fuel verification (item counting, gross defect verification via Cerenkov glow evaluation, and, if possible, item identification). After the closure of the core, the inspector seals it with an IAEA seal.

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

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

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

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

4.3.5. Fuel transfer chambers

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

- A suitable mounting for surveillance equipment that inspectors can use to view identifier numbers of fuel assemblies when the transfer canals are being used for refuelling operations;
- An indexing mechanism on the refuelling machine with a device that can identify the location of each assembly;
- Provision for sealing the canal gate (when applicable) to indicate to the inspectors when it was opened, and an indexing system (where possible) to monitor material shipments between the core and spent fuel pool;
- Provision for inspector access above fuel being loaded into casks or underwater cameras to verify spent fuel identifiers;
- Provision for installation of NDA equipment at key measurement points between the reactor core and spent fuel pool;
- Provision of a surveillance/NDA system to maintain continuity of knowledge of verified spent fuel.

4.4. DECOMMISSIONING

Application of IAEA safeguards continues after the reactor is shut down and preparations for decommissioning begin. The design can consider facilitating activities such as verifying that:

- Nuclear material has been removed from the core and from storage;
- Waste containing nuclear material has been measured and removed;
- Essential equipment has been removed or rendered inoperable.

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

In the context of international safeguards, a facility is considered to be decommissioned when the nuclear material has been removed and the equipment essential for operation has been removed or rendered inoperable. The IAEA uses an ‘essential equipment list’ (of equipment necessary for the declared activities involving nuclear material) to assist it in this determination. Designers are well suited to help the IAEA create such a list, which can be part of the design information provided to the IAEA at an early stage. During early design verification activities, the IAEA can check for the presence of items on the list in addition to their other activities. During the time from when the essential equipment arrives at the facility to when it is verified to have been removed from the site or verified to be non-functioning[19], the facility is considered available for use. In order for the facility to be considered unable to be used, the IAEA must first verify the absence of both nuclear material and the essential equipment (or that such equipment is inoperable).

5. CONSIDERATIONS RELATED TO REACTOR VARIATIONS

This section discusses variations from a typical LEU fuelled LWR. In addition to the considerations covered in Section 4, designers/engineers can also consider how the details described below affect IAEA safeguards implementation.

5.1. MODULAR REACTORS

Designers of small modular reactors (SMRs) for commercial use can consider aspects of these designs related to their safeguardability. Analysis of the safeguardability of a particular SMR design can take into consideration the safeguards equipment that is needed to ensure that safeguards can be implemented in a cost effective manner. SMRs can be expected to have the following characteristics that could affect the implementation of safeguards [20]:

- Low thermal signature: Having a thermal footprint similar to other small scale energy technologies currently deployed in remote locations implies that it will be challenging to use satellite or other forms of remote sensing to verify operation. However, indirect indicators such as lights being on in a remote village or the observed operation of powered equipment in the absence of alternative power sources may be useful.
- Coolant: Use of coolants other than water such as lead-bismuth or sodium does not allow for traditional optical viewing of the fuel in the core or in the spent fuel storage. The IAEA can potentially benefit from access to operator viewing systems for these routine inspection tasks. Authentication of these systems can be considered early on in the design process as it might be technically challenging.
- Number of units per site: One of the potential advantages of SMRs is that multiple individual reactor units can be added sequentially to one larger station, possibly sharing a single control room. However, from a safeguards standpoint, the larger the number of units, the greater the potential need for refuelling and number of discharges per calendar year. It is possible that a common spent fuel pool might be used. These characteristics will need to be considered by the IAEA in determining its inspection approach and inspection frequency, including PIV if an increase in inspection resources is to be avoided or minimized.
- Long life reactor core (sealed vessel): Reduced core access and reduced refuelling frequency makes misuse of the facility and diversion of spent fuel much more difficult. But this will need to be reconciled with the traditional IAEA annual physical inventory of each reactor core, performed when access to the core is possible.[20]

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[19] In reactor safety parlance, different definitions of ‘operable or non-operable’ can apply: ‘functioning’ implies good working order but the calibration and documentation is not approved by the regulator and management, ‘operable’ implies it meets licensing requirements (calibrated and certified) and ‘functional and approved for use’ imply that all required documentation is approved and in place. ‘Non-functioning’ implies the equipment is not useable, irrespective of the calibration and approval documentation status.

[20] Most safeguarded reactor duty cycles are 12–18 months.

— Advanced[21] fuel cycle: In general, the nature of a non-LWR based SMR operating in an advanced fuel cycle will almost certainly be unfamiliar to the safeguards inspectorate and require significant analysis to understand the most effective and efficient safeguards approach. This presents an opportunity for safeguards experts to collaborate with the design team.
— Enrichment: If a design requires uranium fuel enriched above 20%, direct use nuclear material is involved — likely requiring increased safeguards activities.
— Surplus reactivity: A reactor designed for low refuelling frequency would likely have high surplus reactivity and burnable absorbers[22]. Such a core might tolerate target irradiation without affecting key operational parameters that can be monitored and, from an independent observer's viewpoint, neutronic management with burnable absorbers would look similar to neutronic management with target material. Verifying that there is no possibility of access for target insertion or removal can be made a design requirement. Potentially, these concerns can be mitigated with a pre-operation design verification activity by the IAEA coupled with reliable sealing and surveillance measures.
— Fuel element size: Depending on design, the reactor core length might be significantly smaller than conventional designs, leading to the use of shorter fuel elements and two opposing impacts on diversion issues: obtaining a useful quantity requires diverting more items, yet the small size tends to facilitate item concealment. These fuel types can be considered similarly to CANDU or PBMR pebble fuels. Reduced refuelling frequencies and sealed cores can mitigate some of the problems.
— Spent fuel storage geometry: Smaller fuel elements would possibly need to be stored vertically for cooling purposes, with a strong economic incentive to stack fuel and reduce the storage footprint. This geometry potentially challenges the current safeguards inspection activities owing to lack of direct line visibility of fuel elements from above. In one current approach, the operator packages a group of elements in a basket for ease of handling and transport, and the IAEA places the seals on the baskets at the packaging location instead of at the storage location.

5.2. ON LOAD REFUELLED REACTORS

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

Safeguards considerations include provision for:

— Maintaining continuity of knowledge on the core with radiation sensor based core discharge monitors and bundle counters [14];
— Facilitating IAEA verification and maintaining continuity of knowledge of irradiated fuel placed in layers for storage;
— Remote monitoring of IAEA equipment to verify its proper operation.

5.3. PEBBLE BED AND PRISMATIC FUELLED HTGRs

In addition to using nuclear reactors for generating electricity, research and development and isotope production, it is important to note that a high temperature gas cooled reactor (HTGR) can be used for other

[21] Here, 'advanced' can imply innovative fuel designs, use of minor actinides, fast reactor designs, or some combination of these.
[22] Some safeguarded reactors are already using such fuels.

commercial applications, such as those utilizing very high temperature process heat. Designing characteristics relevant to safeguards into the facility at an early stage will be important to maintaining flexibility in monitoring nuclear material inventory and flow when these reactors are deployed (e.g. in petrochemical and chemical processing, fertilizer production or crude oil refining), especially if they are integral to the associated industrial application.

5.3.1. Pebble fuelled HTGRs

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

- The seal and surveillance systems for the reactor core and irradiated pebble fuel storage vessels may be directed at the access hatches to those areas, rather than the vessels themselves, since they are in high radiation areas. This implies that design verification activities take on more importance.
- The IAEA will likely use fuel flow monitors to verify the fuel transfers to and from the associated pebble fuel storage vessels and reactor vessel(s). The fuel flow monitor will count, verify and discriminate spent pebble fuel from fresh, irradiated and damaged pebble fuel, and graphite pebble moderator. Access for installation and maintenance could become an interesting design challenge.
- IAEA seals may also be applied to the fresh pebble fuel storage drums and the pebble feed hopper(s) in the fresh fuel handling area. The designer can provide adequate space for attaching, replacing and servicing the seals.
- The IAEA likely will use NDA techniques for verifying fresh (unirradiated) pebble fuel casks that are the same as those currently used for verifying fresh nuclear fuel containing LEU and uranium oxide fuel (i.e. gamma spectroscopy combined with passive and active coincident neutron counting). The NDA techniques can be complemented by surveillance, containment and monitoring and unattended monitoring. The selection and optimization of this equipment will be dictated by the pebble fuel size, geometry and radionuclide content (i.e. ^{235}U, ^{233}U, plutonium and thorium). Two square metres of space is adequate for most of these IAEA systems and the power requirements are expected to be less than typical office electrical power needs. Design consideration can also be given to communications cabling for unattended operation.

5.3.2. Prismatic fuelled HTGRs

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

- IAEA seals may be applied to the fuel pit covers in the fresh fuel storage area and in the gas cooled spent fuel storage pits if dry storage is used. If spent HTGR fuel is stored in a pool, seals on the fuel would not normally be used.
- If the core or spent fuel cannot be presented easily for verification, then a radiation based fuel flow monitoring system would likely be used to count and verify the irradiated HTGR fuel as it is transferred from the reactor core to the spent fuel storage area, and to detect undeclared reverse transfers of fuel. If the spent fuel storage area is difficult to access (e.g. gas cooled dry storage pits), the fuel flow monitor, possibly in combination with dual surveillance, containment and monitoring measures, would be used to maintain the continuity of knowledge of spent fuel in storage. The fuel flow monitor will be designed to count, verify and discriminate between dummy fuel, fresh fuel, irradiated core fuel and fully irradiated spent fuel. The designer can include the safeguards equipment and physical infrastructure in the design optimization.
- Equipment that has been used for verifying fresh (unirradiated) prismatic HTGR fuel is similar to the NDA equipment that the IAEA uses to verify LWR fuel containing LEU and uranium oxide fuel (MOX). The optimization and selection of this equipment will be dictated by the nuclear material content of the new prismatic HTGR fuel designs (i.e. whether they contain LEU, HEU, plutonium, thorium and/or ^{233}U).

5.4. MOX FUELLED LWRs

Fresh mixed plutonium and uranium oxide fuel, also known as MOX (mixed oxide) fuel, is more safeguards sensitive than natural uranium or LEU fuel, particularly for reconstitutable[23] fresh assemblies, as it contains unirradiated direct use material. A more stringent safeguards approach is therefore usually required for MOX assemblies. Receipt, storage and movements within a reactor facility can be closely monitored in order to maintain continuity of knowledge of the fresh MOX fuel. After it is used to power an operating reactor, the fuel contains substantial amounts of fission products and is considered irradiated direct use material, similar to irradiated LEU fuel — and safeguards might be adjusted accordingly. The following safeguards considerations can be taken into account:

- Measurement or surveillance of fresh MOX fuel under water can require more stringent[24] surveillance, containment and monitoring measures and IAEA verification than fresh LEU fuel in storage because of the plutonium content. Emerging technologies for NDA of MOX fresh and spent fuel are currently under development. Partial defect NDA on irradiated fuel is a more difficult technical challenge for measuring thermal reactor generated plutonium than for fast reactor generated plutonium.
- Consideration can be given to minimize fresh MOX fuel storage time at the plant and to providing means for easily sealing the fresh MOX fuel separately within the storage.
- Consideration can be given to applying more stringent surveillance, containment and monitoring measures to fresh MOX transfer pathways, including radiation detectors for nuclear material flow monitoring.
- Spent fuel storage surveillance, containment and monitoring of MOX fuel is consistent with the non-MOX spent fuel items for a reactor facility under IAEA safeguards. It may be more efficient to cover both the dismantling station and the location of spent fuel storage in the spent fuel pool with single surveillance, containment and monitoring using surveillance when wet storage is used.

5.5. RESEARCH REACTORS AND CRITICAL ASSEMBLIES

Numerous research reactor concepts have been developed and deployed around the world. Their design and flexibility are far more diversified than is the case for power reactors. While the small scale of research reactors and critical assemblies (RRCAs) might suggest that a research reactor is not an important fuel cycle facility, they are a potential acquisition path that the IAEA monitors carefully. Their characteristics offer additional possibilities (potential acquisition paths) for the undeclared production of nuclear material or diversion of declared nuclear material compared to the baseline case [21–23].

Safeguards considerations for RRCAs include:

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

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[23] Fuel assembly designs can include a requirement that they are easily disassembled for replacement of defective fuel pins at the reactor site.

[24] More stringent implies use of more surveillance, containment and monitoring measures and more frequent measurements with improved measurement uncertainties.

Specific safeguards issues to consider for RRCAs include:

- HEU or plutonium fuel in critical assemblies can still be considered ‘unirradiated’ even after use since the irradiation times can be so short that the radiation levels drop quickly after use.
- Stores of loose items containing uranium or plutonium for research activities may be present, which can complicate the material accountancy approach by not being amenable to item counting or measurement.
- HEU may be present for use as targets for the production of medical isotopes such as molybdenum-99 (^{99}Mo).
- Even after extensive use, the enrichment of HEU fuel that was 93% enriched at the beginning of use often still exceeds 20% enrichment at end of use, and is considered by the IAEA to be ‘highly enriched’.
- The possibility to store large quantities of fresh fuel including HEU, ^{233}U or plutonium at an RRCA facility.
- The need to monitor fuel and target loading/unloading activities much more frequently, although for much smaller quantities than those found in larger reactors.
- The possibility to irradiate targets of thorium (to produce ^{233}U) or ^{238}U (to produce ^{239}Pu), to produce direct use material.
- The use of MOX fuel (covered in Section 5.4).
- Separation of plutonium from fresh fuel can be easier than separating plutonium from irradiated fuel.
- Fissile material production in an RRCA can be optimized if the core is loaded with a ‘driver’ fuel to maintain criticality, and surrounded by a ‘blanket’ fuel containing a target material. Consequently, the IAEA can choose to pay close attention to potential diversion from stores of depleted, natural and LEU at an RRCA.
- The possibility of remote monitoring being used in a cost effective manner to reduce inspector activity on-site and yet maintain or improve safeguards effectiveness. One example of this approach is the use of an advanced thermohydraulic power monitoring system that can independently assess coolant flow and heat extraction to calculate plutonium production in the core. This system can be mounted on the primary core coolant loop in a non-penetrating manner.
- Fewer sensitive or proprietary issues for RRCAs exist compared to LWRs that allow more opportunity for safeguards data transmission off-site, live video feeds, monitoring of reactor power levels or other characteristics of safeguards interest.
- The need for IAEA measures to verify the declared usage of hot cells.

5.6. NEXT GENERATION TECHNOLOGY

The next group of Generation IV reactors offer an opportunity to develop or adapt the in-line safeguards measurement or monitoring currently applied to some on-line refuelled reactors. Process monitoring or operational transparency [24] can make more complete use of the facility operator’s process instrumentation as an additional safeguards measure. Concerns regarding independence of the results from the operator’s control and data authentication are areas of current R&D.

Consideration can be given to the fact that many NDA measurement techniques are dependent on the geometry of the fuel or container, and the heterogeneity or homogeneity of the nuclear material inside the container, including any burnable neutron poisons (which are generally burned up in irradiated fuel). Reducing the variation in the positioning of the item being measured can reduce measurement uncertainties.

If fuel movements are performed without human access and access to fuel storage locations are similarly limited, remote monitoring of the fuel movements by reliable, redundant systems can reduce the need for on-site inspections.

Consideration can be given to improving the automated tools used to collect and review data from multiple sensors, including the necessary infrastructure that connects sensors to electronics, than to the computer systems and on to off-site inspector review stations. Designers can help to eliminate common mode failure paths and can recommend suitable levels of redundancy and backup power to avoid loss of safeguards knowledge during the operating lifetime of the reactor.

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

A major difference of safeguards interest would be the potential co-location of a spent fuel processing facility with the reactor facility. The major safeguards and security advantage of co-locating the reactor, reprocessing and fuel fabrication is the reduction of the transportation between sites of the nuclear materials compared to other nuclear energy systems. However, a bulk (re)processing facility would require more intrusive safeguards measures than the reactor type item accounting facility and unless the two facilities can be easily proven to be separate and distinct, both would receive more intrusive application of safeguards.

Similar concerns exist when pin replacement capability is available on a reactor site. Clear segregation of any hot cells with pin handling equipment from the rest of the nuclear material handling and storage facilities will allow the hot cells to be placed under more stringent safeguards measures without affecting most of the facility's item accounting status.

5.7. GENERATION IV LIQUID FUELLED (MOLTEN SALT) REACTORS

For liquid fuelled (e.g. molten salt) reactors, designers should be aware that such reactors cannot be considered item facilities. Beyond pebble bed reactors, which have countable numbers of semi-distinguishable items, more stringent nuclear material accountancy measures will likely be required to verify the quantities, locations and movements of the nuclear material. These measures can include, but are not limited to, fuel flow monitors, seals, video surveillance, the use of sensors to trigger other sensors, more accurate NDA measurements and sampling plans that select additional items for verification. Most of this instrumentation does not yet exist and a significant R&D effort can be expected.

5.8. FAST REACTORS

Reactors with a fast neutron spectrum are designed to use nuclear material more efficiently by recycling the plutonium found in irradiated fuel and by using more of the ^{238}U to breed plutonium. As such, fast reactors generally have larger amounts of plutonium present in the fresh and irradiated fuel than is found at LWR facilities. Additionally, some can use HEU driver fuel. From a safeguards perspective, unirradiated plutonium and HEU receive greater attention than irradiated fuel containing plutonium. Therefore, fast reactor facilities are likely to be subject to more frequent inspections involving more measurements or more surveillance, containment and monitoring measures. However, the plutonium produced in the depleted uranium blankets of fast reactors has very limited build in of plutonium isotopes beyond ^{239}Pu. Consequently, it is more straightforward to accurately measure with existing NDA approaches. Similarly, the plutonium that grows into the irradiated HEU driver assemblies is mostly ^{239}Pu, and therefore they are easier to measure than LWR irradiated fuel.

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

— Early provision of design information before it is finalized;
— Early discussion of possible safeguards measures;
— Provision of additional information by the State regarding nuclear facilities and activities related to the fuel cycle;
— Hardened, secure storage for plutonium, HEU or transuranic fuel;
— Advanced, redundant surveillance, containment and monitoring systems;
— Continuous, unattended NDA to monitor fuel movements that can distinguish between fissile and fertile and non-nuclear material items;
— The implications of minor actinide bearing fuels on the implementation of safeguards are not well understood and are likely to require R&D [25];

— Clear segregation of any hot cells and pin handling equipment from the rest of the reactor facility to allow them to be placed under more stringent safeguards measures without affecting the majority of the facility's item accounting status.

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ABBREVIATIONS

These abbreviations are commonly used in international safeguards, but are not necessarily used in this introductory publication.

AP	Additional protocol (INFCIRC/540 (Corrected))
CoK	Continuity of knowledge
DA	Destructive analysis
DIQ	Design information questionnaire
DIV	Design information verification
HEU	High enriched uranium
HTGR	High temperature gas cooled reactor
IAEA	International Atomic Energy Agency
INFCIRC	IAEA information circular
KMP	Key measurement point
LEU	Low enriched uranium
LOFs	Locations outside facilities
LWR	Light water reactor
MBA	Material balance area
MOX	Mixed oxide
NDA	Nondestructive assay
NGSS	Next generation surveillance system
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
PIT	Physical inventory taking
PIV	Physical inventory verification
RRCA	Research reactor or critical assembly
RSAC	Regional system of accounting for and control of nuclear material
SBD	Safeguards by design
SMR	Small modular reactor[1]
SRA	Safeguards regulatory authority
SSAC	State system of accounting for and control of nuclear material
UI	Unannounced inspection

[1] This abbreviation (SMR) has also been used for ‘small or medium sized reactor’ in other IAEA publications.

Annex I

TERMINOLOGY

Safeguards has developed its own lexicon and applies specialized meanings to many words in common everyday usage. This annex offers simple definitions for this terminology. Some definitions in safeguards usage include metrics or examples. More complete definitions as well as translations of these terms into eight languages can be found in the IAEA Safeguards Glossary [5].

GENERAL

safeguardability. The degree of ease with which a nuclear energy system or facility can be effectively and efficiently placed under international safeguards.[1]

short notice random inspection. An inspection performed both on short notice, i.e. less advance notice, e.g. 24 hours, is given by the IAEA to the State than that provided for under para. 83 of INFCIRC/153 (corrected), and on a date chosen randomly.

unannounced inspections. An inspection performed at a facility or a location outside facilities for which no advance notice is provided by the IAEA to the State before the arrival of IAEA inspectors.

NUCLEAR MATERIAL

direct use material. Nuclear material that can be used for the manufacture of nuclear explosives components without transmutation or further enrichment.

high enriched uranium. Uranium enriched to 20% ^{235}U or more.

holdup. Nuclear material deposits remaining in and about process equipment, interconnecting piping, filters and adjacent work areas.

low enriched uranium. Uranium enriched to less than 20% ^{235}U.

mixed oxide. A mixture of the oxides of uranium and plutonium.

scrap[2]. Rejected nuclear material removed from the product stream, containing nuclear material that is economic to recover and recycle.

waste[2]. Rejected nuclear material in concentrations or forms which do not permit economic recovery and which is designated for disposal.

NUCLEAR INSTALLATIONS AND EQUIPMENT

heavy water. The highly enriched form of water (>99.5% D_2O, where D denotes the isotope of hydrogen of mass number 2).

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[1] From FIG/PRPP working group.

[2] INFCIRC/153 (corrected).

heavy water reactor. A power reactor moderated by heavy water. A prominent example is the Canadian deuterium uranium (CANDU) type reactor.

item facilities. Nuclear facilities where all nuclear material is contained in identifiable items (e.g. fuel assemblies), the integrity of which remains unaltered during their residence at the facility.

locations outside facilities. Locations containing small quantities of nuclear material outside of the principle nuclear facilities. Typical examples include universities, medical hospitals or small research companies.

off-load fuelled power reactor. A reactor which is (re)fuelled while it is shut down and the generator(s) disconnected from the power grid.

on load fuelled power reactor. A reactor which is refuelled while operating and producing power.

safeguards essential equipment. A list of equipment, systems and structures essential for the declared operation of a facility. *Safeguards* essential equipment is often different from *safety* essential equipment.

NUCLEAR MATERIAL ACCOUNTANCY

authentication. Measures providing assurance that genuine information has originated from a known source (sensor) and has not been altered, removed or replaced.

book inventory[4] of an MBA. The algebraic sum of the most recent physical inventory of that material balance area and of all inventory changes that have occurred since that physical inventory was taken.

continuity of knowledge . Assurance that the safeguards relevant data (e.g. identity and integrity of the item, item contents or flow and inventory of nuclear material) remains valid.[3]

declarations. Information submitted to the IAEA by a safeguards authority.

design information. A comprehensive description of the facility and its operation relevant to safeguards submitted to the IAEA by a State.

inventory verification. An IAEA safeguards inspection activity involving a physical nuclear material inventory within a material balance area carried out to verify the operator's book inventory of nuclear material present at a given time within that material balance area.

key measurement point.[4] A location where nuclear material appears in such a form that it may be measured to determine material flow or inventory. 'Key measurement points' thus include, but are not limited to, the inputs and outputs (including measured discards) and storages in material balance areas.

material balance area.[4] An area in or outside of a facility such that: (a) the quantity of nuclear material in each transfer into or out of each 'material balance area' can be determined; and (b) the physical inventory of nuclear material in each 'material balance area' can be determined when necessary, in accordance with specified procedures, in order that the [nuclear] material balance for IAEA safeguards purposes can be established.

material balance period. Term used to refer to the time between two consecutive physical inventory takings.

material unaccounted for.[4] The difference between the book inventory in the facility records and the physical inventory.

---

[3] Usage illustrated in the Safeguards Glossary, but not defined.

Non-destructive assay. Measurement of the nuclear material content, or the elemental or isotopic concentration of an item, without producing significant physical or chemical changes in the item.

nuclear material accountancy. The practice of nuclear material accounting by the facility operator and, in addition, the verification and evaluation of this accounting system by a safeguards authority and/or the IAEA.

physical inventory.[4] The sum of all the measured or derived estimates of batch quantities of nuclear material on hand at a given time within a material balance area, obtained in accordance with specified procedures.

remote monitoring. A technique whereby safeguards data from equipment installed in a facility and operating unattended are transmitted off-site via communications networks for review and evaluation.

safeguards approach. A set of nuclear material accountancy, containment, surveillance and other measures chosen by the IAEA for the implementation of safeguards in a given situation.

safeguards regulatory authority.[4] The State's primary coordinating body responsible to ensure effective implementation of IAEA safeguards**.** This authority may or may not include the regulatory authority.

unattended monitoring. Non-destructive assay or containment and surveillance measures, or a combination, that operates for extended periods without inspector intervention.

SURVEILLANCE, CONTAINMENT AND MONITORING

containment. Structural features of a nuclear facility or equipment which enable the IAEA to establish the physical integrity of an area or item by preventing undetected access to or movement of nuclear or other material, or interference with an item, IAEA safeguards equipment or data.[5]

seal. A tamper indicating device used to join movable segments of containment in such a manner that access to the contents without opening of the seal or breaking of the containment is difficult.

surveillance. The collection of information through inspector and/or instrumental observation aimed at the monitoring of the movement of nuclear material or the detection of interference with containment and tampering with IAEA safeguards devices, samples and/or data.

tampering. Interference in an unauthorized and undeclared manner to physically defeat a containment and surveillance device.

---

[4] INFCIRC/153 (corrected).

[5] This definition differs from that generally used in safety.

Annex II

DIQ INFORMATION

The following information is written at an introductory level for an audience unfamiliar with IAEA design information questionnaires (DIQs). Official templates are available from the relevant IAEA Department of Safeguards country officer or from the IAEA Headquarters in Vienna.

Reactor DIQ information includes as a minimum:

- Facility name, location, address, owner, operator, status, purpose, etc.;
- Facility description, including general flow diagrams;
- Rated thermal output, electrical output;
- Number of units (reactors) and site layout;
- Reactor type;
- Type of refuelling (on or off load);
- The reactor core's U enrichment range and Pu concentration;
- Moderator;
- Coolant;
- Blanket, reflector;
- Types of fresh fuel;
- Fresh fuel enrichment (^{235}U) and/or Pu content;
- Nominal weight of fuel in elements or assemblies;
- Physical and chemical form of fresh fuel;
- Reactor assembly details: e.g. types, cladding, structural details, number of fuel, control and shim elements;
- Description of fresh fuel elements: e.g. chemical form, dimensions, number of pellets, cladding, bonding;
- Provision for element exchange in assemblies (for each type);
- Basic accounting units (e.g. fuel elements, assemblies);
- Means of nuclear material identification;
- Other nuclear material in the facility;
- Schematic flow sheet identifying measurement points, storage/inventory locations;
- Expected inventory/capacity;
  - Fresh fuel storage;
  - Reactor core;
  - Spent fuel storage;
  - Other locations;
- Reactor load factor;
- Reactor core loading (number of elements/assemblies);
- Refuelling details (quantity, time interval);
- Burnup (average/maximum);
- Whether the irradiated fuel is to be processed or stored;
- Nuclear material handling details, including:
  - Layout;
  - Storage plans (drawings);
  - Staging areas;
  - Transfers (including equipment such as refuelling machines and cranes);
  - Routes followed by nuclear material;
- Reactor vessel details, core diagram, flow diagrams (drawings);
- Average neutron flux in core (thermal and fast);
- Instrumentation for measuring neutron and gamma flux;
- Irradiated fuel details:
  - Storage method, capacity;
  - Cooling periods;
  - Handling and routes followed;

- Equipment;
- Description of transport casks;
- Maximum activity of fuel/blanket;

— Nuclear material testing areas, including equipment available, shipping containers;
— Basic measures for physical protection;
— Basic measures for radiation safety including rules for inspector compliance;
— Description of nuclear material accountancy and control:

- Facility ledgers, reports;
- Source data;
- Nuclear loss and production in-reactor;
- Shipping/receiving;
- PIV procedures;
- Methods for corrections and adjustments;
- Surveillance, containment and monitoring features;
- Measurement points, measurement methods, level of accuracy, calibration details;
- Procedures to access nuclear material;

— Optional information the operator considers relevant to safeguards.

Annex III

IDENTIFYING SAFEGUARDABILITY ISSUES

This Annex[1] describes a facility safeguardability analysis approach. It can be used as a structured approach to understand and identify potential safeguards issues. If the operator is building or modifying a standardized facility design for which a well understood safeguards approach exists, the effort to analyse its safeguardability will likely be very modest. However, it may be possible to make existing safeguards tools and measures more efficient with slight modifications to the design, configuration or operating procedures.

A greater effort to assess facility safeguardability might be warranted for facilities that include novel design features or that present particular safeguards challenges. The design team can include an international safeguards expert to help the team prepare for interaction with the safeguards authority and/or the IAEA. Innovative designs that are different from those for which IAEA safeguards approaches are established can present safeguards problems that could be considered by the designer, who could help mitigate them or help accommodate innovative safeguards tools and measures.

Potential safeguards issues can arise from design differences to:

— Utilize different isotopic, chemical or physical forms of the nuclear material;
— Create additional or alter existing diversion paths;
— Create different nuclear material categories for measurement;
— Alter nuclear material flows or pathways;
— Increase the difficulty of design information examination and verification;
— Impede the IAEA's capability to verify that diversion has not taken place;
— Create a new or alter an existing potential for the facility to be misused.

The following screening questions are designed to highlight safeguards relevant issues in a facility design.

TABLE III–1. FACILITY SAFEGUARDABILITY ASSESSMENT

Facility safeguardability assessment screening questions	
1. Does this design differ from the comparison design/process in ways that have the potential to create additional diversion paths or alter existing diversion paths?	Yes/No
1.1. Does this design introduce nuclear material of a type, category or form that may have a different significant quantity (SQ) or detection time objective than previous designs (e.g. mixed oxide rather than low enriched uranium, irradiated vs. unirradiated or bulk vs. item)?	Yes/No
1.2. Does this design layout eliminate or modify physical barriers that would prevent the removal of nuclear material from process or material balance areas (e.g. circumvent a key measurement point (KMP)?)	Yes/No
1.3. Does this design obscure process areas or material balance area (MBA) boundaries making surveillance, containment and monitoring or installation of measurement and monitoring equipment more difficult?	Yes/No
1.4. Does this design introduce materials that could be effectively substituted for safeguarded material to conceal diversion?	Yes/No

[1] Reproduced with permission from: BARI, R.A., et al., Facility Safeguardability Assessment Report, Pacific Northwest National Laboratory Report, PNNL-20829 (October 2011).

TABLE III–1. FACILITY SAFEGUARDABILITY ASSESSMENT (cont.)

Facility safeguardability assessment screening questions	
2. Does this design differ from the comparison design in a way that increases the difficulty of design information examination and verification by IAEA inspectors?	Yes/No
2.1. Does the design incorporate new or modified technology? If so, does the IAEA have experience with the new or modified technology?	Yes/No
2.2. Are there new design features with commercial or security sensitivities that would inhibit or preclude IAEA inspector access to equipment or information?	Yes/No
2.3. Do aspects of the design limit or preclude inspector access to, or the continuous availability of, essential equipment for verification or testing?	Yes/No
2.4. Are there aspects of the design that would preclude or limit IAEA maintenance of continuity of knowledge (CoK) during the life of the facility?	Yes/No
3. Does this design/process differ from the comparison design/process in a way that makes it more difficult to verify that diversion has not taken place?	Yes/No
3.1. Does this design lessen the efficiency of physical inventory taking (PIT) by the operator or the effectiveness of physical inventory verification (PIV) by the IAEA?	Yes/No
3.2. Does this design impair the ability of the operator to produce timely and accurate interim inventory declarations or of the IAEA to perform timely and accurate interim inventory verification (IIV)?	Yes/No
3.3. Does this design impede timely and accurate inventory change measurements and declarations by the operator and verification by the IAEA?	Yes/No
3.4. Does this design impede the introduction of or reduce the usefulness of other strategic points within the material balance area (MBA)?	Yes/No
4. Does this design differ from the comparison design in ways that create new, or alter existing, opportunities for facility misuse or make detection of misuse more difficult?	Yes/No
4.1. Does this design differ from the comparison facility/process by including new equipment or process steps that could change the nuclear material being processed to a type, category or form with lower significant quantity (SQ) or detection time objectives?	Yes/No
4.2. If the comparison facility safeguards approach employs agreed upon short notice visits or inspections, measurements or process parameter confirmations, would this design preclude the use of, or reduce the effectiveness of, these measures?	Yes/No
4.3. Do the design and operating procedures reduce the transparency of plant operations (e.g. availability of operating records and reports or source data for inspector examination or limited inspector access to plant areas and equipment)?	Yes/No

Annex IV

MATRIX OF SAFEGUARDS DETAILS FOR CONSIDERATION

The following matrix in Fig. IV–1 is drawn from the references and the bibliography and is intended to be illustrative rather than comprehensive. It is available from the Division of Concepts and Planning in the IAEA Department of Safeguards as a spreadsheet and can be sorted according to the designer's interests.

Design features that have safeguards relevance are listed in the left hand column.

The other column headings denote:

- — Five project phases (preconceptual design, conceptual design, preliminary final design, construction and operation);
- — General, widely applicable considerations;
- — Access related (layout or infrastructure);
- — Reactor operations processes (related to fresh fuel, reactor operations, irradiated fuel, spent fuel transfer, interim storage of irradiated fuel);
- — Type of reactor (LWR, small, RRCA, Gen IV, MOX fuelled, on load);
- — Types of safeguards measures (design information verification, accountancy, surveillance, containment and monitoring, measurements, data collection and inspections).

A preliminary sorting according to these categories has been begun as an example. It is assumed that each site or reactor design will have specific details that would build upon this preliminary list of considerations and categories.

	Project phases							Access		Processes					Type of facility						Safeguards measures					
	Conceptual design	Basic design	Final design	Construction	Operation	Decommissioning	General	Layout (rooms +access)	Infrastructure	Fresh fuel	Reactor operations	Irradiated fuel (SF)	SF transfer	Interim storage	LWR	Small (modular) reactors	Research reactors	Generation IV reactors	Reactors with MOX fuel	On load reactors	DIV	NM accountancy verification	C/S	Measurements	Data collection	Inspections
Fuel paths are simple and clear																										
Organize fuel transport so it is easy to distinguish fuel from non-fuel																										
Organize fuel transport so it is easy to distinguish routine from non-routine movements																										
Minimize access points in barriers around nuclear material																										
Provide access for inspectors to verify barrier is still intact																										
Minimize radiation exposure to inspectors																										
Select equipment locations that protect equipment																										
Select equipment locations to minimize impact on operations																										
Provision of structures for maintaining sensors (ladder, platform,...)																										
Provide adequate illumination and adequate viewing angles																										
Facilitate inspector activities																										
Provision of supportive facilities and services (changing rooms, inspector's office space, etc.)																										
Clearly label equipment relevant to safeguards																										
Physical protection of seals from accidental damage																										
Unique identifiers or labels for nuclear material items																										
Easy to read identifiers or labels for nuclear material items (and adequate illumination)																										
Tamper proof identifiers or labels for nuclear material items																										
Authenticated identifiers or labels for nuclear material items																										
Ability to collect data on site, but analyze off site																										
Minimize need to revisit site ro resolve questions																										
Facilitate transmission of safeguards information off site (seperate network, inspector)																										
Protect sensitive or proprietary information																										
Support for unattended and remote monitoring																										
Authentication of data (sensors)																										
Reduce vulnerability to equipment failures (e.g. reliable, redundant, battery backed up)																										
Layout of storage of fuel to allow progressive verification and sealing of groups of assemblies without affecting nuclear material already under seal																										
Adequate space, support, and illumination to handle, identify, and conduct measurements on fuel																										
Arrange fuel in store to minimize need to move fuel to access specific assemblies																										
Suitable mounting for permanent and temporary sensors (camera,...)																										
Inspector use of automated readout of location and assembly being moved																										
Ability to seal fuel transport paths/equipment																										
Fresh MOX fuel loading monitoring capability (surveillance from delivery till start-up reactor)																										
Provision for fresh MOX segregation																										
Arrangements for sealing the nuclear material in the core (e.g. the missile shield or reactor slab)																										
Mounting of monitoring/surveillance during core opening activities verification, e.g. capability to see tops of assemblies, very deep core																										
Provide for in core fuel verification capability																										
Provision for monitoring discharges (core discharge monitors, bundle counters, surveillance, etc.)																										
Maintain water quality & clarity in pools																										
Easy to apply C/S to Used Fuel Storage & Shipping Areas																										
Arrangements for mounting surveillance equipment																										
Room lighting selected to avoid UV light interference with ICVD imager (Cherenkov Glow)																										
Storage racks in a single layer permits viewing of top of each assembly/readout of identifier																										
Provision to seal lower layers in fuel store, if multiple layers																										
An indexing system to identify specific assembly locations from fuel handling control point (automated)																										
Water clarity maintained to facilitate identification and measurements of assemblies																										
Provision for NDA verification in SFP for all types of fuel present																										
Monitoring of of fuel transfers (as much as possible in remote mode)																										
How does inspector verify fuel assembly reconstitution ?																										
Nuclear material storage times at reactor should be minimized, if possible																										
MOX fresh fuel containers sealing arrangement																										
The layout of the pond should allow complete monitoring/surveillance																										
Provision for transfer cask/flask monitoring equipment (infrastructure, active support from the operator, for installation and use, ...)																										
Provision for monitoring spent fuel transfers																										
Infrastructure at dry storage for containment, monitoring, surveillance, including layout & design of casks/silos																										

FIG. IV–1. Matrix of safeguards details for consideration by designers or operators.

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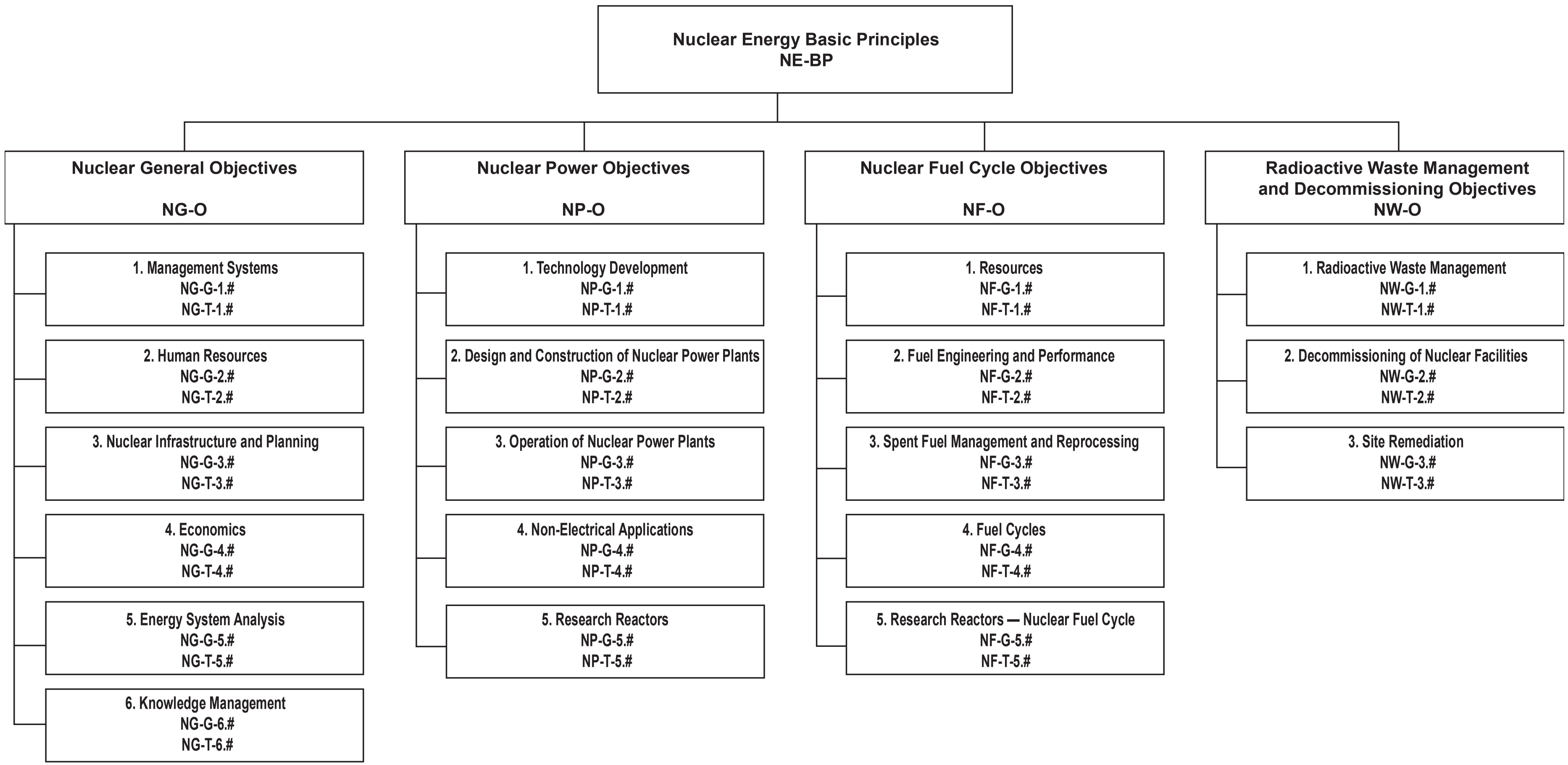

Key

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