NON-PROLIFERATION AND SAFEGUARDS BY DESIGN CONSIDERATIONS IN THE WATSS RECYCLING PROCESS

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Abstract

The recycling of spent nuclear fuel followed by the transmutation of actinides in a waste-burner reactor brings several advantages over the open cycle, in terms of both legacy waste management and fuel availability for the new reactors. It may also bring long-term proliferation resistance and more manageable application of safeguards over time. This is at the heart of the Moltex project at the Point Lepreau site, with its WAste To Stable Salt (WATSS) recycling facility and Stable Salt Reactor – Wasteburner (SSR-W).

Although the recycling of spent nuclear fuel has been hampered in North America by proliferation concerns, the WATSS process presents some inherent proliferation resistance characteristics such as its unsuitability to separate plutonium from minor actinides and lanthanides. The end product of the combined facility is depleted in plutonium, which removes concerns about the potential attractiveness of wastes. Also, the small footprint of the facility, with the process in hot cells with well-defined physical barriers, is suitable for the application of containment and surveillance provisions.

Different features of proliferation-resistance and safeguards application will be integrated in the design process of a WATSS facility in application of a “safeguards by design” concept that leverages inherent characteristics of the recycling process. Early considerations of these aspects will help improve the level of assurance that this kind of facility would not be suitable for proliferation purposes and contribute to the effectiveness of multinational verification activities.

1. Introduction

Reprocessing and recycling of used nuclear fuel are generally considered to be sensitive activities in terms of proliferation since early technologies for these activities could be suitable for the production of weapons-grade material. Proliferation concerns related to reprocessing have largely been shaped by the US policy, essentially after the strict nuclear policy of the Carter administration in the late 1970s. Since then, the once-through open fuel cycle has been privileged as a nuclear waste management framework in the United States although a number of other countries either have, or continue to, reprocess used fuel. A recent report of the US National Academies of Sciences, Engineering and Medicine addresses the topic of advanced reactor fuel cycle issues and concludes, with regards to potential recycling options, that “the once-though fuel cycle is the baseline, and any new fuel cycles should have advantages over that baseline for them to be deployed” [1]. It is therefore important for a wider acceptance of spent fuel recycling options to highlight a high level of assurance that the material and technology would be used for peaceful purpose only.

Canada ratified the *Treaty on the Non-Proliferation of Nuclear Weapons* (NPT) in 1970 and concluded its Comprehensive Safeguards Agreement (CSA) with the International Atomic Energy Agency (IAEA) in 1972 [2] as well as an additional protocol (AP) in 2000 [3]. The cornerstone of these high-level political engagements refers to the assurance for the international community that the country will not divert nuclear material or technology towards a nuclear weapons program. For nuclear weapons states as defined in the NPT, such as the United States or United Kingdom, the concept of non-proliferation safeguards relates to the means of protecting their nuclear material from external, state or non-state, adversaries that could use it for the production of weapons. In a non-nuclear weapons state like Canada the rationale for safeguards is essentially geared at preventing that the plant operator itself, or the host nation, develops such a program. In this framework, safeguards are more related to suitable assurance provisions than to the defence against a threat and a sub-section of nuclear security.

Under Canada's Nuclear Safety and Control Act, the Canadian Nuclear Safety Commission (CNSC) has the mandate to ensure conformity with Canada's international obligations with respect to nuclear energy, including the international safeguards agreement [4]. The requirements within the Safeguards and Non-Proliferation area of the CNSC licensing and compliance framework are described in the regulatory document REGDOC 2.13.1, *Safeguards and Nuclear Material Accountancy* [5]. Those requirements are organized in four specific areas: Nuclear material accountancy and control, Provision of access and assistance for verification activities, Provision of design, operational and other information, and finally Provision for support for safeguards equipment and seals [4], [5].

As highlighted for example in a recent white paper from nuclear regulators in two European countries [6], there are strong incentives to address safeguards provisions at an early stage of the design phase (safeguards by design approach – SBD) rather than applying potentially costly retrofits and/or unforeseen engineered measures. This SBD approach is described and promoted in the IAEA "International Safeguards in Nuclear Facility Design and Construction" report [7].

A framework for the consideration of a wide range of design features in support of safeguards obligations and high-level requirements can be provided by an approach influenced by the safety concept of "defence in depth" (DiD).

2. Application of several levels of non-proliferation assurance provisions

The overarching purpose of non-proliferation safeguards regime is "verifying that (special fissionable material as described in the agreement) is not diverted to nuclear weapons or other nuclear explosive devices," as mentioned in Article 1 of the *Agreement between the Government of Canada and the IAEA for the application of Safeguards in connection with the NPT* [2]. In terms of assurance that there is no diversion of nuclear material for proliferation purposes, several independent levels of provision can be considered, that form a robust and coherent package of guarantees. As suggested in the introduction, these levels of provision could be compared to the levels of DiD as applied in the fields of nuclear safety and security, and a certain level of parallel can be drawn between these concepts although a direct relationship would hardly be relevant.

A first level of non-proliferation guarantee relates to the deterrence for a state to engage in a nuclear weapons program. This essentially refers to its commitments in the framework of the NPT, including the commitment to adhere to an inspection and control regime, as well as other geo-political considerations and security assurance provisions.

A second level of guarantees relates to the detection of a potential nuclear weapons program at declared or undeclared facilities. These aspects are covered through the inspection regimes relevant to respectively the CSA and the AP between the state and the IAEA.

A third level of guarantees begins to relate to non-proliferation features of a specific facility and especially to inherent proliferation resistance characteristics of the design of the facility. These inherent characteristics may or may not affect safeguards requirements as described in the two following paragraphs but can nevertheless contribute to the overall assessment by the IAEA, as discussed in the following section. It is important at this point to highlight that although the concepts of "non-proliferation" – preventing that nuclear material or technology would be used in a nuclear weapons program – and "safeguards" – the verification process that this kind of diversion does not happen – are generally aligned, they may be supported by different sets of provisions. Besides, their criteria may be very different as will be discussed in the following chapter.

The fourth level of guarantee is provided by the "containment and surveillance" (C&S) component of safeguards provisions, which relates to the limitation of diversion routes and the early detection of diversion attempts.

The fifth level refers to the accountancy of nuclear material through the management of a book inventory in close cooperation with the CNSC and periodic physical inventory verification activities by the IAEA.

The different levels described above form a comprehensive framework to identify non-proliferation assurance provisions. Specific considerations across the five levels are reported in Table 1.

The different categories of "Proliferation resistance relevant intrinsic design features" reported in Appendix 1 of the GEN IV White Papers on Proliferation Resistance and Physical Protection (referencing design features in [8]), or at least those that are related to the fuel cycle facilities and not specifically to the reactor, have helped identify non-proliferation assurance provisions reported in the second column of Table 1.

The "features reducing the attractiveness of the technology for nuclear weapons program" as reported in the white papers are considered in the "inherent proliferation resistance" level, the "features preventing or inhibiting diversion of nuclear material" correspond to "safeguards – containment and surveillance," and the "features facilitating verification, including continuity of knowledge" are associated to "safeguards – nuclear material accountancy." Those three areas are also reported as "material barriers," "technical barriers" and "extrinsic barriers" respectively in the IAEA report on technical features to enhance proliferation resistance of nuclear energy systems [9].

Table 1 Consideration of several levels of non-proliferation assurance and related safeguards provisions.

Non-proliferation assurance level	Non-proliferation assurance provision	Implementation level
Deterrence	Commitments not to engage in a nuclear weapons program	State-level political commitment related to the Non Proliferation Treaty
Detection of state-level program	Detection of Nuclear Weapons program at declared facility	State-level inspection regime related to the Comprehensive Safeguards Agreement with the IAEA
	Detection of Nuclear Weapons program at non-declared facility	State-level inspection regime related to the Additional Protocol
Inherent proliferation resistance	Avoid the use of enriched uranium	Facility options and design
	Limitation of the isotopic grade of plutonium	Facility options and design
	Limitation of the chemical purity of NM	Facility options and design
	Limitation of the potential for the technology to produce weapons-useable NM	Facility options and design
Safeguards - C&S	Limitation of the transport of NM to and from the facility	Facility options and design
	The facility has few points of access to NM, especially in separated form	Facility options and design
	Fissile material in produced fuel is difficult to extract	Facility options and design
	Fuel assemblies are large and difficult to dismantle	Facility options and design
	Adequate support for IAEA surveillance equipment	Facility options and design / Operator procedures
Safeguards - NM Accountancy	Comprehensive accounting of NM	Operator accountancy system (in close cooperaton with CNSC)
	The inventory and flow of NM can be specified and accounted for in the clearest possible manner	Facility options and design
	NM remain accessible for verification to the greatest practical extent	Facility options and design
	Adequate support for IAEA verification activities	Facility options and design / Operator procedures

Each identified option is associated with a reference to the implementation level and corresponding stakeholder responsibility. The provisions referred as “facility options and design” highlight opportunities for SBD considerations, design features that have the potential to increase the “safeguardability” of the facility. According to [9], safeguardability is defined as the degree of ease with which a system can be effectively (and efficiently) put under international safeguards. It is a property of the whole nuclear system and is estimated on the basis of characteristics related to the involved nuclear material, process implementation and facility design [9].

As highlighted in Table 1, there are several areas where facility options and design have the potential to affect the safeguardability of the plant. It essentially relates to the inherent proliferation resistance (largely through technological choices at the early stages of the project) as well as features facilitating C&S and accounting provisions (design options during the facility design process).

3. Inherent proliferation resistance aspects

As mentioned earlier, the criteria for non-proliferation and safeguards considerations may be very different. It is acknowledged that in terms of safeguards provisions, the concept of "weapons-grade material" is meaningless and plutonium, whatever its isotopic composition or chemical purity, should be considered as direct-use material. This essentially refers to the fourth and fifth levels of non-proliferation assurance as described in the preceding section.

It is however important to highlight that even though it is assumed for safeguards purposes that any composition of plutonium could theoretically be used to make an explosive device, not all are similarly attractive for a weapons program (see [10] for more comprehensive discussions of this aspect). This distinction highlights that safeguards provisions (represented by the early detection of diversion) and proliferation-resistance features (essentially referring to material attractiveness) may not be fully aligned. Instead, they complement each other to provide means of non-proliferation technical features that could be independent. This could in turn be taken into account by the IAEA in its assessment of diversion risk.

Proliferation-resistance inherent characteristics of nuclear material (whether stemming from its isotopic composition or chemical purity) could relate to technical barriers due to radioactivity, spontaneous neutron production, heat generation and alloying behaviour of the material. The importance of these barriers is highlighted and discussed in [10].

Besides, in a comprehensive approach to a risk-informed assessment, the merits of the combination of spent fuel recycling and transmutation of actinides on the overall reduction of available plutonium in the stockpiles should be considered. This option brings several advantages over the once-through open cycle, including long-term proliferation resistance and more manageable application of safeguards in a long-term perspective.

The attractiveness of nuclear material across different fuel cycles can be quantified on the basis of metrics such as the internationally acknowledged "estimated conversion time," as reported in Figure 1 as a function of the evolution of spent fuel material over its lifetime [11]. These metrics are consistent with the attractiveness categories for the processing phase considered in [12]. Immediately after irradiation and during on-site temporary storage, spent fuel has an estimated conversion time of one month, irrespective of the fuel cycle option. In an open cycle, the conditioning of the wastes for long-term storage decreases the relative proliferation attractiveness of the material by increasing the estimated conversion time to three months as discussed in [11] and highlighted in Figure 1. The waste is then transported to a central storage facility (before or after conditioning), and possibly transported again to a final repository. Figure 1 also reports similar evolution of material attractiveness for the classical approach of a closed fuel cycle (centralized production of MOX with purified Pu following reprocessing of spent fuel, and distribution across a fleet of reactors) as well as a combined recycling – transmutation plant such as the co-location of WATSS – SSR-W facilities.

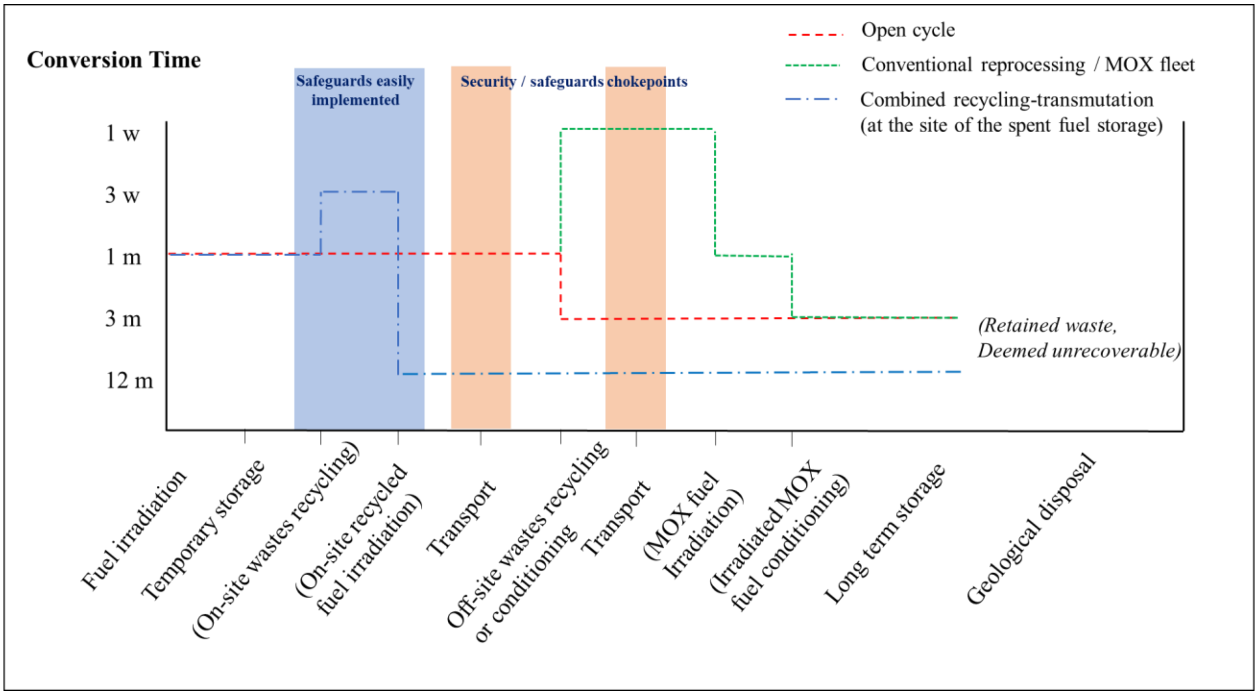

Figure 1 Evolution of the metrics of material attractiveness for proliferation purposes in different fuel cycles [11]. Process stages mentioned between brackets are only relevant for one of the fuel cycles considered. Long-distance transports are security critical chokepoints, whereas processes in a closed facility already under safeguard provides easier implementation of complementary safeguards measures.

As highlighted in Figure 1, the proliferation concerns of the baseline option are not negligible and are actually higher than those related to some closed cycle options at different stages, especially during the security-critical chokepoints represented by long-distance transports and long-term storages, when safeguards provisions are the least effective and the material is the most vulnerable. In comparison, alternative closed-cycle options such as a combined recycling-transmutation process bring considerable opportunities for long-term and comprehensive proliferation resistance. The only trade-off is a slight decrease in the estimated conversion time at a specific stage in the lifetime of the spent fuel, but only for a limited amount of time and in closed facilities already under control, so in the conditions where complementary safeguards measures are the most easily implemented.

4. Safeguards by design features in a WATSS facility

A fundamental feedback from other projects is that very close communication with the IAEA is of critical importance to identify safeguards requirements criteria and validate technical options [6], [13]. This needs to be carried out in a trilateral exchange framework with the state nuclear regulator, the CNSC, but it may not be possible to assure that this could take place while at the same time providing guaranties that the intellectual property related to the design information shared would be protected. This is especially important at the early stages of development when intellectual property is relatively more vulnerable. Alternatively, the facility designer may develop its own knowledge of high-level safeguards requirements and build a framework for the implementation of SBD features, that would be discussed with the IAEA at a later stage.

The objective of safeguards for the WATSS facility, as for other nuclear facilities, is the timely detection of the diversion of one significant quantity of nuclear material. This will preferably be provided by traditional safeguards approaches including material balance areas (MBA) and key measurement points structure, enabling nuclear material accountancy supported by review of operating records, annual physical inventory verification and more frequent interim inventory verifications. This overall process is complemented by C&S measures as well as verifications of the facility design information. However, feedback from safeguarding reprocessing plants [13] highlight that traditional safeguards measures may not meet the objective and "strengthened safeguards" would possibly be required, such as more frequent inspections and evaluation of the nuclear material balance and additional continuity of knowledge provisions. Alternative safeguards provisions such as enhanced physical barrier containment or randomized verification activities [13] could be considered to reduce the burden to both the operator, the IAEA and the CNSC that frequent inspections represent.

In order to determine the most suitable strategy to apply safeguards provisions in a risk-informed manner, we have adopted an approach in which specific emphasis is laid on taking advantage of inherent aspects of the processes. A fundamental step in this approach is therefore to identify the inherent features of "safeguardability" in the three levels of assurance provision in which facility options and design may be relevant. These, as reported in Table 2, could be regarded as proliferation resistance strengths especially in comparison with currently fielded PUREX reprocessing and existing fuel cycles.

Table 2 Inherent aspects of the WATSS process that could be leveraged as safeguards by design provisions.

	Potential for Safeguards-by-Design provisions
Nuclear material (NM) attractiveness	• Low purity Pu / No separation of minor actinides & lanthanides • No need for imported nuclear material • No need for U enrichment
Containment and surveillance measures	• Process in hot cells – well defined area with strong physical barrier and difficult access • Relatively small area with few, easy to monitor, access points • Fuel elements assembled, used and disassembled in the same building complex – difficult to take out • No out-of-facility transport of recycled material
NM accountancy / verification of declared inventory	• Buffer storage of intermediary product: fuel salt in flasks, as Items • Storage of final product: fuel assemblies, as Items

The first point reported in Table 2 essentially relates to the characteristics of the WATSS separation process that makes it unsuitable to separate plutonium from minor actinides, therefore compromising the attractiveness of the material for the production of an explosive device [10]. In addition to that, the remaining presence of lanthanides interferes with the metal properties of actinides and further degrades the attractiveness of the material for potential diversion. Although the distinctions based on plutonium purity are hardly considered in terms of safeguards application, as discussed earlier, these considerations can still be highlighted in the framework of an independent level of non-proliferation assurance.

Other important features in terms of the limitation of the potential attractiveness of nuclear material is the fact that the SSR-W does not require the use of enriched uranium and especially HALEU as most other SMR designs. This avoids requirements not only for enrichment facilities but also for cross-border transport of nuclear fuel. Besides non-proliferation, this is also a considerable advantage in terms of fuel availability and sovereign independence.

The two first points of the C&S features leverage the fact that the footprint of a WATSS process is considerably lower than traditional reprocessing facilities. In terms of operating space, the controlled atmosphere hot cell represents a secure space with strong physical barriers, extremely limited access points and no possibility of human entry. All inputs and outputs are via one of two easy to monitor airlocks. All these elements contribute to the notion of “enhanced physical barrier containment” as a possible novel safeguards approach as described in chapter 8 of the US DoE report on *Advanced Safeguards Approaches for New Reprocessing Facilities* [13].

The concept of SBD is already being considered for the proposal of an integrated WATSS – SSR-W plant featuring the third and fourth points highlighted in the level of assurance related to C&S consideration. Fundamentally, the combination of WATSS and SSR-W facilities in an integrated plant is already a strong feature to advance safeguards (and security) provisions through a design option as it considerably limits a critical diversion path.

Regarding the potential structure of MBAs, a single MBA for a process line would allow to take the full advantage of the well-defined and hardly accessible processing area, without transfer of bulk material from one MBA to another. Nuclear material would be transferred from one MBA to another only as items, easier to account and to track. This takes advantage of the fact that fuel salt in the SSR-W reactor is in individual fuel elements unlike in most other molten salt reactor designs.

5. Conclusions

It has been highlighted that several considerations in the design of the WATSS fuel recycling process can be leveraged to support non-proliferation safeguards. The consideration of several layers of non-proliferation assurance, in an approach comparable to the defence in depth in safety or security, represents a comprehensive framework featuring design provisions across fields as varied as lowering the attractiveness of nuclear material or easing inspection activities. Overall, the combination of these provisions brings compelling assurance that the facility will be suitably placed under safeguards control and alleviates proliferation concerns possibly stemming from its nature.

6. Glossary of acronyms

AP	Additional Protocol / Protocol additional to the CSA
C&S	Containment and Surveillance
CNSC	Canadian Nuclear Safety Commission
CSA	Comprehensive Safeguards Agreement
DiD	Defence in Depth
HALEU	High Assay Low Enriched Uranium
IAEA	International Atomic Energy Agency
MBA	Material Balance Area
MOX	Mixed (Pu-U) oxide fuel
NM	Nuclear Material
NPT	Non-Proliferation Treaty
PUREX	Plutonium-Uranium reduction extraction
REGDOC	Regulatory Document
SBD	Safeguards by Design
SMR	Small Modular Reactor
SSR-W	Stable Salt Reactor – Wasteburner
US DoE	United States Department of Energy
WATSS	WAste To Stable Salt

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