POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

System Analysis Approaches in the Nuclear Safeguards of Liquid-Fuelled Molten Salt Reactors

A Safeguardability Assessment Tool and NDA Applicability through the Italian Flag Methodology

TESI MAGISTRALE IN MANAGEMENT ENGINEERING – INGEGNERIA GESTIONALE

AUTHOR: DANIELE BATANI

ADVISOR: PAOLO TRUCCO

CO-ADVISOR: STEFANO LORENZI

ACADEMIC YEAR: 2024-2025

1. Introduction

Liquid-fuelled molten salt reactors (MSRs) represent a promising nuclear technology offering inherent safety advantages and operational flexibility. However, their bulk-fuel operational modalities, with possible online refuelling and reprocessing, represent a fundamental departure from traditional item-based fuel systems. The reactors will inherently have a non-null Material Unaccounted For (MUF), and a biased protracted defect could go unnoticed. Moreover, unlike conventional bulk-handling facilities, the reactors both create and consume fissile material, presenting unprecedented challenges for the implementation of international nuclear safeguards [1] [2]. As MSR development accelerates globally, with dozens of designs at various stages of development, the question of how to effectively and efficiently place these reactors under International Atomic Energy Agency (IAEA) safeguards becomes increasingly critical. Evaluating the reactor's design compatibility with the safeguards approaches is necessary for a successful safeguards-by-design (SBD) approach [3]**. Safeguardability is the degree of ease with which a nuclear energy system can be effectively and efficiently placed under international safeguards** [4] and is a key evaluation metric of the SBD process [3, 4]. This thesis addresses this gap by developing a comprehensive Safeguardability Assessment Tool (SAT) that integrates system analysis methodologies to quantify qualitative safeguardability assessments at early design stages, establishing a foundational framework for SBD implementation in all reactors, and specifically liquid-fuelled MSRs. In accordance with the ENDURANCE project's goals, in which this thesis evolves, the research bridges designers and safeguards inspectors by enabling early-stage evaluation, identifying critical research needs for inspector instrumentation development, and thus minimising retrofit costs.

2. Research Context

The Non-Proliferation Treaty provide the legal framework, and the IAEA's safeguards system enacts the verification of non-diversion of nuclear materials to military purposes. However, these mechanisms were designed for conventional fuel cycles and power generation facilities. The emergence of Generation IV reactors, particularly MSRs employing liquid fuels, necessitates paradigm shifts in safeguards philosophy. No fit-for-all safeguards solution exists for MSRs, given the vast differences between designs and reactor families [2]. In some designs, the continuously circulating liquid fuel and online reprocessing create additional diversion paths [5], measurement and modelling uncertainties that challenge conventional signature interpretation, material verification, and MBAs' closures. For instance, the removal of fission products such as Cs-137 would impede the use of such elements for burnup verification [6, 1]. Some designs will use the Th-U cycle, not previously safeguarded and presenting unique challenges [7]. The MBAs will have to be defined such that even biased and partial defects can be statistically detected [6]. New modelling tools and increased modelling accuracies are needed to integrate the technology's peculiarities and prevent the compounding of modelling uncertainties with the measurement uncertainties [6, 2]. The significant needed change throughout the whole safeguards approach needs to be addressed at a moment of maximum leverage and freedom of action, rather than hoping for post-hoc retrofits [3]. Finally, much design information is unavailable [5]. MSRs also present opportunities: the inspectorate has the chance to implement (near) real-time remote accountancy, which must, however, be done through cooperation with the operator for sharing instruments. The reactors are characterised by a high-temperature and high-corrosivity, for which the instruments must be adapted. The instrumentation already deployed on the reprocessing plant seems adaptable for the described needs [8].

For these reasons, it follows that Safeguards must be embedded in the design considerations, through SBD, and an evaluation of this process is needed, hence a safeguardability assessment. The research questions addressed by this thesis regarding safeguardability are: (1) What safeguardability attributes must liquid-fuelled MSRs possess to enable effective and efficient international safeguards implementation? (2) How can these qualitative attributes be quantitatively assessed to inform both designers and inspectors? (3) To what extent can the existing non-destructive assay (NDA) techniques and instrumentations adapt to liquid-fuelled MSRs, and what knowledge gaps must be addressed to ensure NDA applicability?

The central hypothesis is that synthesising existing safeguardability assessment frameworks, tailored to MSR-specific characteristics and integrated with system analysis methodologies, can provide actionable guidance for both the designer and inspectorates during early project phases.

2. Methodology

The research employs an integrated methodology combining document analysis, literature synthesis, expert consultation, and application of two system analysis approaches adapted from decision and evidence theory. The underlying goal is to produce actionable knowledge that can be put to use by the stakeholders of the ENDURANCE project, such as implementing SBD in a dialogue between designers and the European Commission's inspectors.

State-of-the-Art Synthesis and Safeguardability Assessment Tool Development

The initial phase involved a comprehensive literature review of existing safeguards practices, proliferation resistance evaluation frameworks, and safeguardability assessment models. Sources included IAEA and GIF evaluation frameworks [8, 9, 10, 11], and the facility safeguardability analysis developed by US National Laboratories [4]. From this synthesis, existing safeguardability evaluation attributes were identified, reorganised hierarchically, and tailored to address liquid-fuelled MSR-specific challenges, including bulk-fuel handling, continuous online salt reprocessing, and inventory determination uncertainty. This was done by performing a comprehensive review of the expected safeguards challenges stemming from the MSRs' technical peculiarities [5, 6, 1, 2]. The resulting SAT comprises a layered hierarchical structure, enabling flexible application from policy-level to inspector-focused assessments, with attributes distributed across the three branches of a safeguards approach: Design Information Verification (DIV), Nuclear Material Accountancy (NMA), and Containment and Surveillance (C/S).

Multi-Attribute Utility Theory (MAUT) for Expert Preference Elicitation

MAUT, drawn from decision analysis, was selected as a fit methodology to convert the qualitative safeguardability assessment into a quantitative framework by capturing expert preferences through the weighting of the SAT attributes and the establishment of related evaluation parameters. The MAUT approach involves: (1) establishing a utility function that aggregates attribute scores, (2) eliciting expert weights reflecting each attribute's importance to overall safeguardability, and (3) deriving a composite safeguardability score. This methodology enables differentiated emphasis on attributes critical for liquid-fuelled MSRs (such as salt composition measurement capabilities) versus generic reactor features. It also enables the traceability, granularity, and aggregation of the information. **The actual decision-maker's preferences can be captured once the attributes are provided, but it is thought that only the inspectors have sufficient safeguards experience, and thus, their preferences are to be captured instead to provide actionable knowledge to designers.**

Dempster-Shafer Theory (DST) and the Italian Flag Methodology for Uncertainty Propagation

Systems are characterised by uncertainty, which is composed of randomness, fuzziness, and incompleteness of the information. The pre-conceptual design phase context is characterised by substantial incompleteness and uncertainty in technical information. In a holistic approach (in which each design feature is considered to be achieved through a process that is both a whole and part of a system), the DST (Evidence Theory) was used as a framework for the application of the Italian Flag methodology to manage these epistemic uncertainties while propagating expert judgment through hierarchical dependencies [12]. The applicability of the methodology to safeguardability assessment has been previously studied [12]. The Italian Flag methodology employs a decision tree structure representing the expert assessments of process success at multiple levels of detail, utilising belief functions and plausibility measures from DST rather than classical probability**. The framework allows for an effective transposition of the qualitative opinion of experts into quantitative success intervals**. The evidence supports a set of hypotheses, among which one is taken to be true. A proposition about where the truth resides is made, and this proposition is evaluated by the expert. The expert associates a so-called **belief mass to each**

proposition, meaning the expert's interpretation of how likely the truth is to be found within the evaluated set of hypotheses.

DST Formalism

The frame of discernment is composed of the different hypotheses ω_i so that $\Omega=(\omega_i), i \in \mathbb{N}$, and is supposedly fully describing the universe (exhaustivity). The truth must lie in Ω. The proposition about where the truth is always made on sets (that can be singletons) and not on individual elements ω_i. For each set A, the expert associates a belief mass m(A) regarding how he considers the available evidence to support the proposition that the truth lies in A. Thus, $m(\emptyset) = 0$ and $\sum$m(A)= 1.

The uncertainty coming from ignorance is modelled in two ways: (1) When belief mass is assigned to non-singleton sets, there is a situation of partial ignorance because no discernment between the hypotheses can be made. Total ignorance is represented by assigning mass to the entire frame of discernment, reflecting a total lack of discriminatory information. Then, m(Ω)>0 (not informative).

The Belief Function is created to quantify the total amount of **belief that the evidence *firmly supports* the proposition** that the true hypothesis lies in *A*.

$$Bel(A) = \sum_{B \subseteq A} m(B) \qquad 1)$$

The Plausibility Function represents the total extent to which one *fails to doubt* the proposition "the truth lies in A". It includes the belief explicitly committed to *A* and the belief committed to larger sets that overlap with *A* and therefore *could* support *A*. **The plausibility is then the belief in the hypotheses contradicting A**

$$Pl(A) = \sum_{C \cap A \neq \emptyset} m(C) \qquad 2)$$

Italian Flag Formalism

The expert evaluates the proposition that the process will be a success. Its opinion is assembled into a single interval **[Bel(A); Pl(A)]** where:

[0; Bel(A)] is the belief of the success of the evaluated process, represented by the colour green. Conversely, [Pl(A); 1] is the doubt or evidence against the success, represented by red.

[Bel(A), Pl(A)] represents only the subsets where the sources do not provide enough specific information to commit to success or failure. The interval represents the uncertainty of the expert on the success of the process, represented by white.

Conflict of evidence

Conflict arises when one source says the answer is A and the other says B, where A and B do not overlap. In the DST, to avoid the loss of belief mass, the conflictual masses are "normalised", meaning they are reassigned to the other sets, which erases the conflict. In the Yager method, conflict is considered to be a source of uncertainty, and thus the conflictual mass is reassigned to the whole frame of discernment, representing a situation of total ignorance. This approach preserves uncertainty explicitly, enabling identification of critical knowledge gaps requiring targeted research efforts.

Open-World assumptions

It is necessary to include open-world assumptions in the DST model, meaning that the scenario cannot be fully understood, and some information is inevitably missing. Ω is no longer exhaustive and the truth can be outside of it, thus $m(\emptyset) \geq 0$. Then, Belief in A, and the belief in its complementary not necessarily sum to 1. Finally, conflictual masses can now indicate that the truth is not in Ω.

Dependencies and Propagation

In the flags' propagation, the attributes must be characterised by necessity, sufficiency, and dependency. The first two evaluate how the success in one attribute will influence the success of the father. The latter evaluates how the success/failure of one sub-process will influence the success of the other.

The propagation is done pairwise by expert elicitation, Yager, and by averaging the flags of the subprocesses (average of pairs). Mathematically, a contingency table is created in which the cells are the multiplications of the belief masses, assigned to the intersection of the two sets. Conflict arises when the intersection is the empty set.

Application of the methodologies to the study of the NDA Applicability to MSRs

The Italian Flag was concretely used to assess the applicability of NDA instrumentation to the Molten Salt Fast Reactor (MSFR) paper reactor. The interviewed experts from the EC's Joint Research Centre have experience as Euratom inspectors and NDA instrumentation R&D. The Expert elicitation process begins by compiling the enabling factors (leaf-level of the tree) for an attribute, which are the subprocesses that must be successful for an overall success (necessity). The focus was put on whether material signatures are sufficiently informative and the instruments are accurate enough to enable the qualification and quantification of nuclear material, despite design-induced measurement challenges. The MAUT was selected as an appropriate technique to be applied to the SAT (with attributes at the same level of detail), but it was deemed that the need for identifying knowledge gaps through the Italian Flag methodology was more urgent.

3. Main Results

A Tailored BTC

The inspectorates collect information about the design through forms. For the European Commission, the form is the Basic Technical Characteristic (BTC) (respectively the Design Information Questionnaire, DIQ, for the IAEA). To lay the foundations for the SBD process in ENDURANCE's designs, a BTC tailored to liquid-fuelled MSRs was developed and is to be distributed to the designers to reduce the incompleteness of design information, and thus the uncertainty in the safeguards establishment process (Appendix C).

Comprehensive SAT

The SAT (Appendix F) is developed for each Safeguards branch with close to 200 attributes that cover, for example, the definition of material balance areas (MBAs), accessibility and suitability of key measurement points (KMPs), availability and robustness of NDA signatures, and calibration and verification of instruments. The layered structure provides a flexibility that allows both high-level strategic assessments and granular technical evaluations, addressing diverse stakeholder needs without requiring uniform information maturity. The SAT is conceived both as (1) a checklist to support designers in identifying safeguards-relevant design choices (respecting the need established in [4]), and (2) a backbone for quantitative methodologies such as DST. The *NDA applicability* branch is used as a proof-of-concept, and as such, the layered structure has been presented, and the evaluation parameters are present. Further development for the other branches is needed.

Other Deliverables

Other safeguardability assessments in the literature [9] [13] have been reworked. The *Matrix of safeguards details for consideration* presents 54 attributes that have been reorganised according to the safeguards branches and the SBD phases. Additional attributes have been added from the literature [5], and a rationale for the attributes is provided to help the designer (increased effectiveness, efficiency, or ease in establishing the safeguards approach) (Appendix D). The scores of relevance to safeguardability of those same attributes, affected in [13], have been ranked to provide a basis for the MAUT's weight attribution (Appendix E).

The Italian Flag Application's results

Much of the modelling needed for safeguards purposes is also operational data needed for the operator. A success is expected, but the inaccuracies of modelling are considered. *The NM in the facility is accurately modelled*: [0.6;0.8]. This is a direct subprocess of the applicability of NDA, evaluated together with the *Nuclear Material can be accurately qualified/quantified by NDA*.

Attribute/process	Expert	Yager	Average
Informative neutron signature	[1;1]	[1;1]	[0.97; 1]
Informative gamma signature	[0.7;1]	[0.68; 1]	[0.68; 1]
Informative calorimetry signature	[0.5; 0.5]	[0.49; 0.5]	[0.49; 0.5]
The design enables different measuring techniques to complete each other	[0.5; 1]	[0.5; 1]	[.66; .94]
The NM quantity and geometry allow the instrumentation to detect partial defects.	[0.3; 0.7]	[0; 1]	[.27; .78]
The design enables the instruments to be kept in the best working conditions.	[0; 1]	[0; 1]	[0; 1]
The NM can be accurately qualified/quantified (by NDA)	[0.3; 0.7]	[0; 1]	[.53; .84]
NDA is applicable to the MSFR	[0.4; 0.7]	[0.3; 0.8]	[.51; .82]

Table 1: Summary of the main Italian Flags for each propagation method

The first impact left by the final Italian Flag is the strong green portion, seemingly against the literature. A lot of white would be expected. The semantic construction of the branches intrinsically reduces the white when the aggregation is done.

Some of the evaluated aspects MUST be resolved to operate the reactor from a safety point of view (such as what is described as "operational data need"). So, it makes sense to assume that a success would be achieved in these attributes before the safeguards approach would have to be designed. Moreover, one of the 1st level subprocesses is directly evaluated and not propagated, limiting the influence of the propagation method on the final flag. **The white part of the flag provides valuable information. It is a crucial incompleteness of information that must be resolved to achieve a high safeguardability of the design. The red represents the inapplicability of some approaches, the inability of detecting partial or biased defects with the current ITV accuracy needs, and, substantially, the need for a paradigm shift in how the safeguards approach is conceived**. Discrepancies between the propagation methods are both expected and not so significant at this stage. The identification of the reasons for the discrepancies can provide valuable information.

4. Conclusions

A proxy for the successful implementation of SBD is the quantification of the design's safeguardability. The SAT developed herein represents a consolidated effort to regroup fragmented safeguards knowledge from international literature and to adapt it for the unique operational characteristics of the bulk-handling MSRs. Unlike historical safeguards practice, which was applied retrospectively upon design completion, the SAT enables prospective assessment during conceptual design phases when modifications can be incorporated without significant retrofit costs. The tool's layered architecture provides flexible assessment at multiple levels of detail, enabling both policy-level evaluations and granular inspector-focused assessments, thereby serving the diverse stakeholder needs within the safeguards ecosystem.

The MAUT framework translates subjective expertise into measurable utility functions that respect both the traceability and aggregative logic essential for decision-making. This will help the designers in a safeguardability self-assessment. The Italian Flag methodology provides a structured means to quantify inherently qualitative expert judgments about safeguardability. The application of the Italian Flag methodology must be extended to the whole SAT, as the Expert Elicitation process will contribute to the validation and finalisation of the model. **Future work will systematically test the SAT against the ENDURANCE designs**. Trade-offs in the implementation of safeguards-friendly design features vs. retrofit costs should be computed.

References

[1] e. a. Worrall, "MOLTEN SALT REACTORS AND ASSOCIATED SAFEGUARDS CHALLENGES AND OPPORTUNITIES IAEA-CN-267".

[2] et al. Donald N. Kovacic, "Safeguards Challenges for Molten Salt Reactors".

[3] INL, "Implementing Safeguards-by-Design," 2010.

[4] PNNL, "Trial Application of the Facility Safeguardability Assessment Process to the NuScale SMR Design," 2013.

[5] GIF, "GIF Molten Salt Reactor PR&PP White Paper," 2023.

[6] ORNL, "Planning for Material Control and Accounting at Liquid-Fueled Molten Reactors," 2024.

[7] ORNL, "Safeguards Technology for Thorium Fuel Cycles," 2021.

[8] S. E. et al., "Survey of prospective techniques for molten salt reactor feed monitoring," *Annals Of Nuclear Energy*, 2024.

[9] IAEA, "Volume 5 of the Final Report of Phase 1 of the INPRO".

[10] IAEA, "International Safeguards in the Design of Nuclear Reactors".

[11] GIF, "Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems".

[12] GIF, "Addendum to the Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems," *OECD Nuclear Energy Agency*, 2007.

[13] G. Renda, "Applying System Analysis and Risk Informed Approach to Support the IAEA Safeguards and non-proliferation regimes, PhD thesis," 2002.

[14] C. H. H. Y. Seungmin Lee, "Approach to Prioritizing Safeguardability Evaluation Parameters Using the Delphi Method and Analytic Hierarchy Process," *Esarda Bulletin*, no. 66.

[15] PNNL, "Guidelines for the Performance of Nonproliferation Assessments".