

SAFEGUARDS ENVELOPE: THE FIRST STEPS

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ABSTRACT

The possibility exists for real time accountancy and assay of nuclear materials as they move through a reprocessing facility. This project aims to establish working parameters and local figures of merit to identify possible diversion in real time with minimal operational impact. Factors such as pH, NOX gas concentration, flow speeds and radiation fields are rarely taken into account in safeguards methodologies and will be included to increase the confidence of location and assay of nuclear materials. An adaptable, real data model is being created of the contactors of the Advanced Fuel Cycle Facility and will be analyzed using the appropriate modeling codes. This model will then be subjected to three diversion scenarios and a figure of merit methodology will be utilized to create the operational parameters under which these diversion scenarios would be detected. This analysis for figure of merit methodology will include statistical fluctuations, operator error, and a rudimentary analysis of transient conditions. The long term goal of the project includes expansion universally over the plant, methods of detection without requiring access to proprietary information, and an evaluation of the requirements for future figure of merit methodologies.

Keywords: Safeguards Envelope, Reprocessing, Proliferation Resistance (PR), Multi Attribute Utility Analysis (MAUA)

INTRODUCTION

Nuclear power production cannot exist without a risk of special nuclear material (SNM) proliferation. However, this risk can be mitigated and minimized by the implementation of safeguards into nuclear facilities. If the nuclear power renaissance is to continue its momentum at its current rate, a sister renaissance of safeguards must keep pace. Novel approaches to reduction of proliferation risks must be created based on existing technology and using the tools available today but with a look towards expected future improvements. This paper describes a suggested novel approach that is being studied. Current safeguards cannot address all of the proliferation concerns of nuclear energy today and the growing challenges only renew the importance of improvement. In recognition of these facts, the Advanced Fuel Cycle Initiative (AFCI), Generation IV program (GEN IV), and Global Nuclear Energy Partnership program (GNEP) all state a goal of better safeguards and enhanced proliferation resistance (PR).^{1,2,3} There are several significant areas of risk in nuclear nonproliferation but few garner as much attention by professionals and media as nuclear fuel reprocessing. Reprocessing, beginning with the Rokkasho Reprocessing Plant (RRP) in Japan, is occurring in non-nuclear weapons states (NNWS). RRP is the first commercial reprocessing facility to be under full IAEA safeguards, as all other operating commercial facilities are under EURATOM safeguards in nuclear weapons

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states (NWS). Because of this relatively new development, the comprehensive safeguards agreement with Japan regarding the RRP relies on higher levels of transparency and what other countries may consider proprietary information. Current accountancy techniques are extremely expensive in time and money. As plant throughput increases, these techniques are also becoming fundamentally limited by measurement uncertainty. In preparation for the building of new, possibly internationally owned reprocessing facilities, methods of higher confidence of the assay and location of nuclear material is paramount.

One of the methods that has been discussed and even requested by a comprehensive PR roadmap literature survey is the creation of a safeguards envelope.⁴ The Nuclear Security Science and Policy Institute (NSSPI) at Texas A&M University and the Idaho National Laboratory have begun research into the creation of such a safeguards envelope under the sponsorship of the U.S. DOE Safeguards Campaign. The results of the project study will demonstrate a working model of a small subsection of a reprocessing plant, detect off-normal operations in real time, and determine if those off normal operations have a reasonable probability of being a diversion. Finally, the expected results should aid the International Atomic Energy Agency (IAEA), domestic inspecting entity, and facility operators to effectively and efficiently monitor and verify SNM in a manner that provides minimal intrusion into normal facility operations. This paper discusses (1) the theory of the safeguards envelope in detail, (2) concurrent supporting work in progress and (3) the path forward for the creation of this methodology.

SAFEGUARDS ENVELOPE

The safeguards envelope as envisioned is to be a robust set of operational parameters from which a diversion is less likely if they are not deviated from. However, in the creation of these operational parameters, local PR of the material must be determined, as well as a method to determine on-normal, off-normal, and possible diversion in real time. The local PR of the material will be an established local value that describes the attractiveness to attempting to proliferate the material. A PR close to 1 represents very unattractive circumstances for the proliferator (highly resistant) and a PR value of 0 represents very attractive circumstances. This value is created over a specified material balance area (MBA) which can be scaled from large structures such as a section of a facility to “pipe 248-D.” This local PR is useful in determining where the material becomes more susceptible to diversion during a transient. The method for the identification of possible diversion helps evaluate whether an operator or regulator needs to perform an inspection. Both of these objectives can be completed by creating figures of merit (FoM) methods. Combined, these two FoM methods, Local PR and Diversion Detection, should help determine possible diversions and then identify where the material was most vulnerable during the transient. This method, of course, is not meant to replace material accountancy, containment and surveillance, or physical security, but add another tool to the toolbox of their practitioners in order to increase their respective confidence that no material has been diverted.

The complexity and scope of the creation of the full Safeguards Envelope is a very large problem that is unlikely to be solved in the immediate future. However, the safeguards envelope methodology needs to be in place before further reprocessing plants are brought online, and so should be based on existing methods and ideas from other fields. As a result, the proposed prototype safeguards envelope is expected to pull heavily from already existing and verified

theory. This safeguards envelope will use the concept of the safety envelope, applied in a new direction, use data that already exists in reprocessing facilities, and utilize existing FoM methods.

The concept of a safety, or operating envelope, is well established in nuclear operations. A set of parameters, such that safe operation will result, is established. Subsequently, to ensure safe operation, operating parameters are kept within the prescribed limits. When new operations are considered, they are first analyzed against these limits. If the resulting parameters will be “within the envelope,” the new activity can be approved. In practice, this is codified in the NRC or DOE regulations (for U.S. facilities) and ensconced in the facility technical specifications.^{5,6,7} The allowed actions and parameters in the technical specifications create the operating, or safety envelope. A safeguards envelope, consisting of the parameters and operations such that nuclear material diversion is ruled out, can similarly be established.

There is a significant amount of data available in a reprocessing facility that is commonly not taken into consideration in traditional safeguards. Radiation field spectra and heat generation are useful parameters but pH, NOX gas concentrations, weight of remaining cladding, drastic temperature changes, flow rates, pressure changes, etc. are not regularly considered in safeguards because they are not directly related to the SNM. However, when taken as a whole they create a signal that is very difficult to spoof. These sets of data are already recorded at reprocessing facilities and would not require any additional expense or new equipment. They have simply been unused because they do not directly correlate to the amount of SNM in a local area.

Operating parameters in an appropriate steady state will be determined and they will be entered into a FoM methodology to determine the local PR of the SNM at each location in the reprocessing facility. This local PR will come from attributes determined to be relevant to the difficulty of diverting the material at that point. The derived FoM methodology will heavily rely on existing FoM methods which utilize the multi-attribute utility analysis (MAUA). While previous work has relied on additive MAUA methods, this work will use a multiplicative MAUA methodology similar to that which was developed for intrinsic safeguards analysis for the Indian fuel cycle.⁸

MAUA is a business decision analysis tool developed in 1978.⁹ It has several methods of compiling both quantitative and qualitative factors into a single decision based around the relative sizes of single figures of merit. Each factor is associated with some hurdle or aspect of a decision that must be taken into account. In safeguards, when evaluating proliferation resistance, this typically refers to different levels of risk, time, money, or effort in order to successfully divert material. This can be accommodated in a MAUA analysis to assess the relative PR among various points. These factors are assessed by the creation of a utility function for each factor by the analyst. These utility functions generate a specific value based on their input parameters. These specific values are then weighted and compared to a standard or set of standards. In safeguards, these would represent on-normal, off-normal, and expected diversion path standards. MAUA methods have been applied successfully to evaluate the PR of SNM as a function of time and location in the nuclear fuel cycle with results that were consistent with expert elicitation.¹⁰

Additionally, data from off-normal and diversion simulations will be evaluated to get a grasp of how to identify differences between on-normal, off-normal, and diversion scenarios. The data

points are expected to be placed in a similar MAUA method or even more complex FoM methods discovered when working with MAUA. Examples of how these extra pieces of data can be used for diversion identification are included in the Concurrent Research area of this document. The FoM MAUA method developed will have threshold-based alerts which will allow for operators and regulators to establish times of interest for more detailed inspection. This analysis for figure of merit methodology will include statistical fluctuations, operator error, and a rudimentary analysis of transient conditions. A diversion will cause the local FoMs to shift and trigger one of the above described alerts.

Ultimately, the combination of the Local PR FoM and Diversion Detection FoM should, in real time, identify times of interest that should receive special attention by operators and regulators and furthermore identify specifically where in the facility the lowest proliferation resistance occurred. Of course, this must be done without creating a significant false positive rate, using existing non-proprietary data, and with low computational requirements. While this seems a lofty goal, the successfully employed methods outside of the safeguards community show it to be achievable.

SAFEGUARDS ENVELOPE EXAMPLE

An example of how this would work applied in the most obvious, easy setting and using a very rudimentary approach would a pressurized water reactor using a purely additive FoM with mostly binary choices. A purely theoretical example is presented below, using generic parameters to demonstrate the method. As an example, three material sets are considered: fresh fuel, fuel in the reactor, and irradiated fuel. Attributes for PR could be chosen such as “How accessible is the fuel?” “Radiation in Terms of Dose” “Ability of Unauthorized Fuel Movement to be Detected”. Attributes for detecting expected transient and off-normal conditions might be “Was fuel moved since the last inspection?” “Was the crane in motion when it was not expected to be?” “Was the pressure vessel seal broken?” and “Did any of the radiation alarms show off-normal operation (turned off/spiked/flat-lined perfectly)?”

Weights are be assigned for both the PR method and diversion detection FoMs. A normal operation is considered to establish a baseline PR and then an expected transient scenario would is considered, a refueling outage. Finally, a diversion scenario such as the removal of a central rod from multiple fuel assemblies would be considered. This particular scenario bears special interest because currently there are few ways to detect such a diversion. The weights assigned and the underlying functions to the proliferation resistance are shown below in Table I. In all cases, stealing material would be trivial at PR=0 and almost impossible to steal at PR=1. Table II shows detection of off-normal conditions weights and utility functions.

Table I PR Resistance Method

Attribute	Function	Weight
Fuel Access	% of time accessible	0.1
Radiation in Dose	x/5	0.4
Movement Detection	% detection	0.5

Table II Diversion Detection

Attribute	Function	Weight
Fuel Moved?	Binary (1/0)	0.1
Crane in Motion?	Binary (1/0)	0.3
Pressure Vessel Seal?	Binary (1/0)	0.2
Off-normal alarms?	Binary (1/0)	0.4

The three material cases are then considered in on-normal conditions, with their relative PR presented below in Table III. Then an expected transient is considered, which, during the transient, adjusts the PR value for all three scenarios (Table IV). It was assumed that during the refueling that less attention could be paid to detecting unauthorized movement.

Table III Base PR for MBA

Attribute	Weight	Fresh Fuel	In Core	Spent Fuel
Fuel Access	0.1	0.25	1	0.75
Radiation in Dose	0.4	0	1	0.75
Movement Detection	0.5	0.5	1	0.8
Final Score		0.275	1	0.775

Table IV Refueling PR for MBA

Attribute	Weight	Fresh Fuel	In Core	Spent Fuel
Fuel Access	0.1	0.25	0	0.75
Radiation in Dose	0.4	0	1	0.75
Movement Detection	0.5	0.4	0.8	0.6
Final Score		0.225	0.8	0.675

As expected, the Fresh Fuel category has significantly less PR than the Spent Fuel which is less than the fuel In Core. Furthermore, during transient conditions, the PR all of the groups dropped but both the In Core and Spent Fuel groups dropped significantly more than the Fresh Fuel group. These results are both in agreement with common sense and previous research but demonstrate the method.¹¹ Finally, to consider the diversion scenario, assign a threshold alarm to 0.5 and assume that our adversary is smart: the adversary will successfully spoof logs to always have the crane in motion. The Diversion Detection FoM of the Safeguards Envelope would look similarly to Table V.

Table V Diversion Detection

Attribute	Weight	Normal Refuel	Diversion
Fuel Moved?	0.1	1	1
Crane in Bad Motion?	0.3	0	0
Pressure Vessel Seal?	0.2	1	1
Off-normal alarms?	0.4	0	1
Final Score		0.3	0.7

This shows a diversion detected as a time and point of interest even assuming that a few of the normal tell-tale signs are spoofed. Naturally, if more attributes that are considered, it becomes more difficult to spoof all of the signals or for multiple failures to suggest a diversion may be taking place. A Safeguards Envelope can then be determined by setting operational parameters that optimize detection. At the most basic level, this Envelope insists that operations not take actions which lower the proliferation resistance below a certain threshold. Furthermore, this example is the easiest example using the most simplistic approach: the real task of a reprocessing facility using a more complex model will require more studies.

CONCURRENT RESEARCH

A similar diversion detection safeguards envelope is being developed for gas centrifuge enrichment facilities under the nuclear engineering department at the Massachusetts Institute of Technology and Oak Ridge National Laboratory. This safeguards envelope is expected to follow in similar theory to what was described above but is in very early planning phases. This project, GAMS, may become a sister project to the described safeguards envelope of this paper.¹²

Demonstration of solution monitoring as a parameter to determine the location and assay of nuclear material has been considered and research in that field is still in progress at Los Alamos National Laboratory. In order to meet the growing requirements, a solution monitoring system monitors changes in tank level, density, and temperature to ensure that it is what is expected. The researchers at Los Alamos expect that large use of solution monitoring can help reduce bias errors in material accountancy. It is expected that this method is a forerunner in helping demonstrate the use of additional, existing data and the results will be incorporated into the safeguards envelope as it develops.¹³

The Nuclear Engineering Department of the University of Tennessee is investigating the actual statistical and computational methods used to determine on-normal and off-normal operating conditions in industrial processes using neural network learning. Specifically, this approach uses the auto-associative means, modeling techniques which learn to correct normal relationships among measured variables. The approach in this case is to measure the difference between a simulation and an actual sensor. This approach appears to work very well for well described systems whose transients are well defined and whose simulations are extremely accurate.¹⁴ Additional work in online monitoring was demonstrated to be able to detect diversions in real time using simulated data but still only when compared to an expected, well described model.¹⁵ This method isn't directly applicable to this project, but could be adapted. UT is comparing simulations to sensors where this project would be comparing expected transient behavior from empirical data to whatever current transient or possible diversion is occurring at the time.

SAFEGUARDS ENVELOPE PATH FORWARD

A model is being created of a generic reprocessing facility's contactors in order to determine normal and off-normal operating parameters for several of the normally ignored parameters mentioned above. This model is expected to be compared to the AMUSE, FLUENT, MCNP,

flow diagram and isotopic concentration data that is being developed for the Advanced Fuel Cycle Facility (AFCF) for validation and verification. From this model, operating data sets of particular attributes of interest will be collected for each modeled point and tested for variance. These attributes are to include but are not limited to: concentration of SNM per volume, concentration of SNM per mass, material form, radiation level in terms of dose, chemical reactivity, temperature of the source process, and heat load of the material to be extracted.

A FoM MAUA method will be created to evaluate the PR of the SNM at each point using the attributes and a concrete set of utility functions. This will allow for comparison of relative PR over the entire facility and be able to show the change in PR. This will be benchmarked against expert elicitation to establish validity of the original model.

New models that include transient conditions will be used, if available, or created as needed to determine the expected transient conditions. These transient conditions are expected to include normal plant component failures as well as operator error. Additionally, three diversion scenarios will be developed and simulated. This data will be inserted into the same PR MAUA to show the changes in PR over the course of the transients and diversion scenarios. The data will also be compared to the on-normal conditions to establish a full new FoM MAUA which attempts to detect on-normal, off-normal, and possible diversion conditions with a 95% confidence with a very low (<5%) false positive rate. This may use neural networks, Bayesian statistics, or coupling with anomaly detection codes.

The expected results include a methodology to create a quick, accurate, and concise warning based on the local figures of merit along the process. This information will detail when there was a point of interest and suggest areas in which the PR dropped or where in the process the greatest deviation from the expected normal occurred. This increase in information will not be intimidating, excessive or frivolous and allow for more rapid response to the most vulnerable areas of the plant. This tool is a benefit to both operators and regulators and is expected to have little opposition from either group. This work is not expected to replace current methods of MC&A but work parallel to generate a higher confidence.

Future work will include expansion to a plant wide safeguards envelope that will use data significantly upstream and downstream of the local FoM point to achieve better confidence for each step along a process. As full plant models are created, this methodology will be included to form an integrated whole which will decrease the false positive rate. Advancements in technology will be able to be included in this methodology by the nature of the multiplicative MAUA method. Eventual cost savings could be established by decreasing the amount of sampling required for confidence of the location and assay of nuclear materials. Additional cost savings will be realized if the safeguards envelope can be applied within the above-described full plant model by assisting in the design of sample points. Finally, additional work will be required in the area of the safeguards envelope without the inclusion of state proprietary information, especially if this method is used by IAEA. Online monitoring in real time is realizable today, and it is required that new methods are responsible with their collected data or perform their analyses without the use of state secrets and proprietary information.

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