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Nuclear Safeguards Challenges at Reactors Types That Defy Traditional Item Counting

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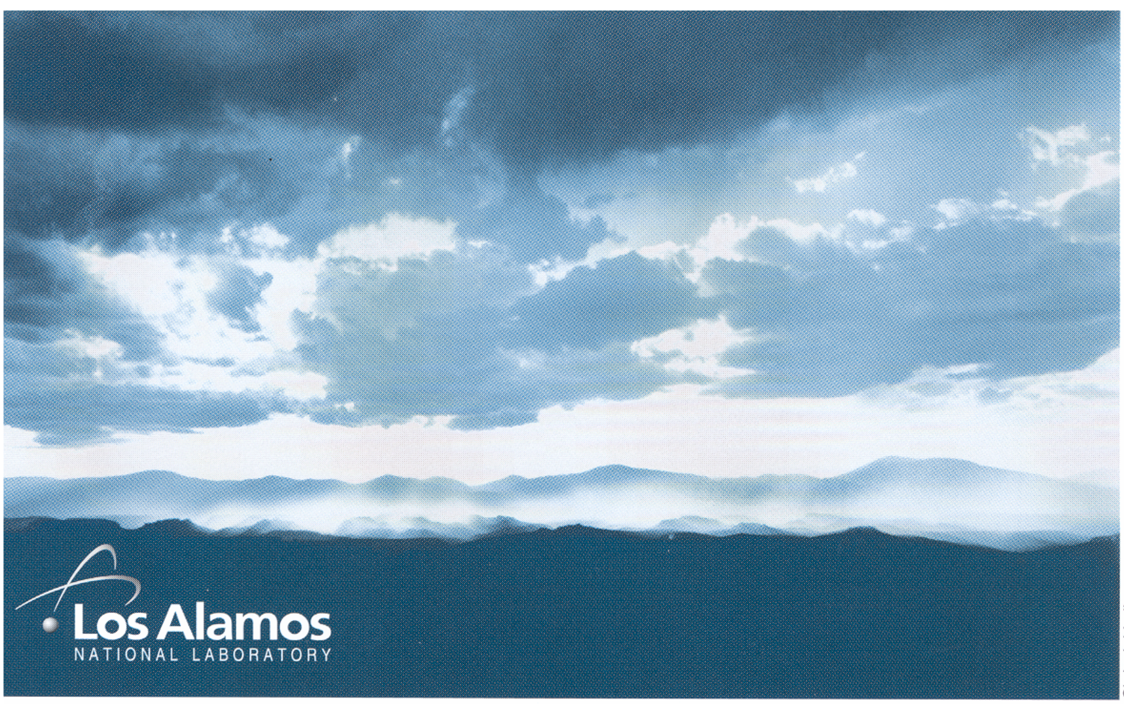

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Abstract

There are reactor types that defy the traditional item accountancy safeguards approach applied to LWRs. Reactors types such as FBRs and PBMRs that prohibit traditional item counting fall into a safeguards gap between item-counting facilities and bulk facilities. At Fast Reactors and Pebble-Bed HTRs the difficulties associated with traditional item counting have given rise to safeguard approaches that rely upon maintaining Continuity of Knowledge (CoK) of containment and surveillance (C/S) data throughout the operational lifetime of the reactor. The reliance on CoK represents an inherent weakness in the safeguards approach; if CoK is lost and cannot be re-established, a facility will potentially remain out of compliance for the duration of its operational lifetime. It is evident that new safeguards approaches are required for these reactor types to mitigate the CoK vulnerability.

At the present time, there are only a few reactors worldwide that cannot be readily safeguarded by item accountancy and C/S. However, future nuclear fuel cycles that are being considered around the globe all include a fast reactor component. For example, the Pebble-Bed HTR is a potentially attractive reactor design for countries with little or no existing nuclear infrastructure. It is clear that the number of reactors posing the unique safeguards challenge associated with systems that do not permit traditional item accountancy will increase in the coming years. Now is the time to consider safeguards alternatives that will remove the excessive dependence on C/S continuity of knowledge to provide the safeguards community with viable alternative safeguards approaches for these reactor types.

Introduction

As the safeguards community prepares for a significant increase in nuclear power production on a world-wide basis and methods for efficiently closing the nuclear fuel cycle are being explored, it is evident that reactor types beyond the typical LWR designs will be deployed. Some of these reactor designs – sodium-cooled fast reactors, pebble-bed high-temperature gas reactors, and molten-salt fueled reactors – pose unique safeguards challenges that prohibit the traditional item accountancy approach favored by the IAEA for reactor safeguards. This paper will present some of the challenges associated with these reactor types and discuss attributes of possible safeguards approaches that may be applied to future reactor systems.

To date, the reactor types of interest in this discussion have either not been commercially developed or exist in small enough numbers that the safeguards approaches are being developed on a specialized per-case basis. As the number of safeguarded reactors in this group increases, the existing ad hoc approach to the safeguards approach will need to be refined and developed to produce a more robust and standardized methodology.

Current Implementation of Reactor Safeguards

Safeguards at nuclear reactors are based upon two fundamental tools to meet inspection goal of detecting the diversion of a significant quantity (SQ) of material within the timeliness period. These tools include item accountancy and containment & surveillance (C/S). Item accountancy is achieved though a combination of book review activities, fresh fuel verification, core verification, and spent fuel verification. The verification activities for item accountancy rely on visual confirmation of item serial numbers and attribute confirmation. For reasons particular to each of the reactor types of interest in this discussion, item accountancy is difficult or impossible to achieve.

Reactor Types of Interest

This discussion will be based upon a spectrum of nuclear reactor designs that by virtue of their design and operation defy traditional item accountancy. These reactors reside in a safeguards approach domain that exists between item facility accountancy and bulk facility accountancy. For lack of a clear safeguards approach, the region between item- and bulk-facility approaches represents a safeguards approach gap. To date, this "gap" has been filled by reliance on CoK.

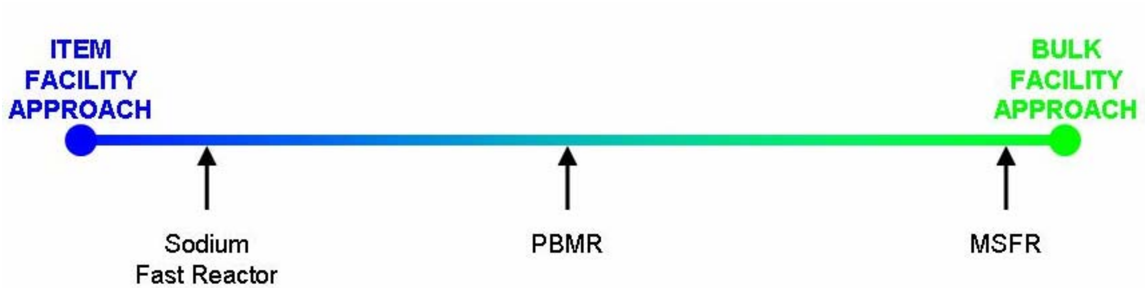

Figure 1. Reactors in the Safeguards Approach Gap

The three reactor types that are under discussion in this report have been chosen to illuminate the limitations of item accountancy approaches for nuclear reactors. This concept is shown graphically in Figure 1. The sodium fast reactor can be marginally addressed as an item facility. The PBMR has properties that make both item accountancy and bulk accountancy possible options. The molten salt fuel reactor (MSFR) must be considered as a bulk facility.

Sodium-Cooled Fast Reactors

Sodium-cooled fast reactors pose challenges to reactor safeguards approaches for a variety of reasons. These stem from the visual opacity of the liquid sodium, the chemical reactivity of sodium, the remote handling of the fuel assemblies and the canning of spent fuel. Under present safeguards at sodium-cooled fast reactors the serial number of a fuel assembly cannot be reverified once the fuel is introduced the reactor system until it arrives at a reprocessing facility and the spent fuel can is opened. Because this reactor types utilizes MOX fuel, the timeliness requirement associated with the safeguards goal must be met without visual verification. Further, because the spent fuel is canned, traditional Cerenkov viewing in the pond cannot distinguish spent fuel from irradiated non-fuel items nor can the technique detect pin diversions.

Pebble-Bed Modular Reactors

Pebble-Bed Modular Reactors (PBMRs) present an interesting challenge stemming from the fact that there are a large number of elements present in the reactor, and that elements are not produced with individual serial numbers. These difficulties are aggravated by the on-line refueling capability of this reactor type. The large number of low-inventory items (5-9 gU/element) that circulate through the PBMR system endow this reactor with characteristics that are akin to both bulk and item facilities. Because of the limited number of units of this reactor type the safeguards approach has yet to be finalized.

Molten-Salt Fueled Reactors

Reactors that employ a liquid phase fuel that is circulated though a "core" have not been commercialized nor do they remain under serious consideration in the GEN-IV project. However, this reactor type is representative of the extreme case where item accountancy cannot be applied. The absence of fuel "items" forces a safeguards approach that is akin to that of a bulk handling facility. This case is demonstrates a scenario where the strong association between reactor safeguards and item accountancy cannot be met.

Safeguards Approaches at Reactors of Interest

For reactor types that defy traditional item accountancy, there are a variety of safeguards approaches available to the inspectorate. Historically, the IAEA has relied upon maintaining CoK for these "difficult" reactors. The reliance on CoK is a risky safeguards methodology – when CoK is lost, significant effort must be expended to recover the lost assurances. The reverification effort may place an undue burden on the facility operator. Because the number of reactors worldwide in this category is low, the long-term ramifications of this approach and the cost of reverification have not yet entered the safeguards approach methodology. As the number of reactors of these types increase, it will benefit the inspectorate to consider new safeguards options. In the text that follows we will consider the following safeguards approaches for reactors of interest:

1. Use C/S and adjunct sensors to maintain CoK over the lifetime of the reactor
2. Force the problem back to item accountancy by using new techniques
3. Treat the reactor as bulk handling facility

Safeguards Approaches at Sodium-Cooled Fast Reactors

C/S and CoK Approach

IAEA safeguards at sodium-cooled reactors have followed the CoK maintenance approach. The reliance on C/S and maintaining CoK over individual fuel items has defined the safeguards approach for this reactor type. This method is reasonably simple – a secondary indicator of fuel flow (gross attribute sensors at key measurement points [KMPs]) is used to perform an item balance over the reactor facility. This option typifies current safeguards approaches at the Monju and Joyo reactors.

Because the loss of CoK can potentially result in a facility being out of compliance for the duration of the operational lifetime, reliance on CoK forces the inspectorate to pursue additional paths in conjunction with this safeguards approach. First, the inspectorate must improve the reliability of both the C/S and sensors used for CoK to minimize the probability of a loss of safeguards data that would result in a loss of CoK. Second, some adequate means of recovering from a loss of CoK must be developed.

The benefit of improving equipment reliability is useful for safeguards in general. However, the number of additional sensors and measures taken to allow for inevitable system failure, to insure that a failure does not result in a loss of CoK, can quickly result in a Byzantine safeguards system. The resulting cost and effort associated with such a system detracts from the overall approach. Despite the application of layered measurements and C/S, the inevitability of failure and subsequent loss of CoK persists in this scenario. The approach does not allow for a means of mitigating the consequence of failure. This is demonstrated by the fact that the IAEA lost CoK at the Monju Reactor during the initial core loading activity. At Monju, the loss of CoK has forced development of new approaches to recover CoK through new reverification measurements.

The development of methods to recover CoK by reverification is a prudent measure, and is ongoing in variety of areas of IAEA safeguards where the primary safeguards approach is reliance on maintenance of CoK (e.g. dry cask storage of spent fuel, Monju reactor core, BN-350 spent fuel transfers to storage). Methods for reverification tend be become highly complex because they need to verify both the correctness of declared activities and preclude the possibility of all imaginable diversion scenarios presented by the particular loss of CoK event.

Reliance on the maintenance of CoK as a safeguards approach forces the inspectorate to employ additional measures to enhance the reliability of the measurement system to prevent a loss of CoK. The resulting number of sensors and methods can produce a complex and expensive safeguards system. As an aggravating factor, the increased complexity of the system can work against the reliability of the approach. In addition, the inspectorate must proactively pursue development of reverification techniques to recover from the inevitable loss of CoK.

Enabling Item Counting Approach

There are technologies that can be applied that would permit more traditional item counting, including serial number verification in core and in off-line cooling tanks, at sodium fast reactors. If it is possible to implement item accountancy through the introduction of an acceptable new technology, the improvement in the resulting safeguards approach warrants the testing and evaluation of the technology. A very promising technology is Under-Sodium Viewing. This ultrasonic viewing technology was developed for the Hanford FFTF in the late 1960's and prototypes were deployed in 1972[1]. The technology has been demonstrated under reactor conditions and has sufficient resolution to permit ready confirmation of serial numbers of fuel assemblies under liquid sodium. Bond, et al recently published a review of this technology [2].

Because spent fuel from sodium reactors is placed in a sealed can prior to introduction to the spent fuel pond, there is no opportunity to close a balance between the fresh fuel storage area and the spent fuel pond. It may be possible to use under-sodium viewing of serial numbers of fuel assemblies in ex-vessel storage combined with CoK between storage and the canning station to generate a verified association between fuel assembly serial numbers and can serial numbers to allow item accountancy. An alternative may be to use a camera to record assembly serial numbers during the canning process.

A second difficulty associated with canned fuel becomes evident when CoK of the spent fuel pond is lost. Cerenkov viewing of canned spent fuel cannot distinguish fuel from irradiated non-fuel nor can it detect pin diversions. Measurement with modified fork detector may be required to verify a spent fuel pond when CoK is lost. Because of Am-241 in-growth and related spent fuel decay issues, a coincidence fork or a specialized active-fork measurement may be required for complete reverification. Study and development would be required to assess the sensitivity of the measurement to pin diversion.

A third reverification option comes from the tomographic imaging technology that has been developed for spent fuel verification. Systems have been developed in Sweden to perform tomographic imaging of spent fuel with impressive results. Other methodologies using lead slowing-down spectrometers have been proposed. Tomographic imaging requires considerable facility infrastructure and equipment overhead. As a result such an approach may not be cost effective for inclusion as a off-normal reverification methodology.

From these few examples, it is evident that it should be possible to pursue safeguards approach number 2 and return Na-cooled reactor safeguards back to traditional item counting.

Safeguards Approaches at Pebble-Bed Modular Reactors

The safeguards approach for PBMR reactors has been under consideration for many years. There are a variety of publications on the matter [3, 4, 5], but there is no publicly available safeguards approach for this reactor type. There is one operating PBMR at Tsinghua University in Beijing China and the facility is under IAEA safeguards. To date safeguards measurements at the facility have been limited to fresh fuel verification. No spent fuel has been discharged from the reactor as of the time of this writing.

PBMRs present two challenges to traditional item counting. First, the individual pebbles do not have serial numbers. Second, a PBMR has a very large number of pebbles in the reactor each with a small material quantity. Values relating to fuel inventories of the three PMBR designs that are operating or under development are listed in Table I. From the values in Table I it is evident that PBMRs, and especially larger designs have inventories more similar to bulk handling facilities than to item counting facilities. Since the PBMR pebble has no serial number, traditional item counting is not possible, even if it were practical to track such a large number of items.

If we consider the safeguards approach options listed earlier, the first option of improving C/S to maintain CoK may be reasonable for the PBMR. Technologies being developed to verify process monitoring equipment might prove applicable to the facility pebble counters in support of CoK. However, for pebbles circulating through the reactor system, there would be no means of restoring CoK in event of a loss of data without considerable development effort.

Table I. Fuel Inventory for PBMRs

Reactor	Rated Thermal Power (MW)	Core Inventory (Pebbles)	Fresh Fuel Uranium Mass (gU/Pebble)	Initial ^{235}U Enrichment (%)	Pu Mass in Equilibrium Discharge Pebble (gPu/Pebble)
HTR-10	10	27,500	5.0	17.0	~0.08
PBMR-400	250	360,000	7.0	8.0	0.154
ESKOM	400	440,000	9.0	9.0	0.114

Considering options 2 and 3 presents an interesting approach for the PBMR. If one constructs a multiple MBA structure at the reactor; the first for fresh fuel storage, the second for the reactor core and pebble circulation system including temporary spent fuel storage, and a third for spent fuel discharge, a hybrid approach becomes possible. This construct is shown in Figure 2. The hybrid approach becomes transparent with a balance between fresh fuel receipts and spent fuel removal. The fresh fuel and spent fuel MBAs can be balanced by verified item counting and attribute verification. The reactor MBA could be handled as a bulk facility. Treating the reactor core area as a distinct bulk accounting MBA allows for the accountancy of the creation and destruction of nuclear material in the reactor in a straightforward manner. Further, the circulation of pebbles in the reactor can be more easily approached from a material process flow perspective that a bulk approach enables. The interface between the reactor area MBA and the spent fuel storage MBA can be developed by implementing a temporary spent fuel storage that is volume limited to prohibit an accrual of greater than 1 SQ (8,000 – 15,000 pebbles at 74% packing density depending upon the reactor design, or 1300 – 2300 liters). An engineered solution to prevent significant accrual of MUF (Material Unaccounted for) in the bulk-handling MBA would greatly reduce the difficulty of hybrid item/bulk facility and may result in a practical safeguards approach.

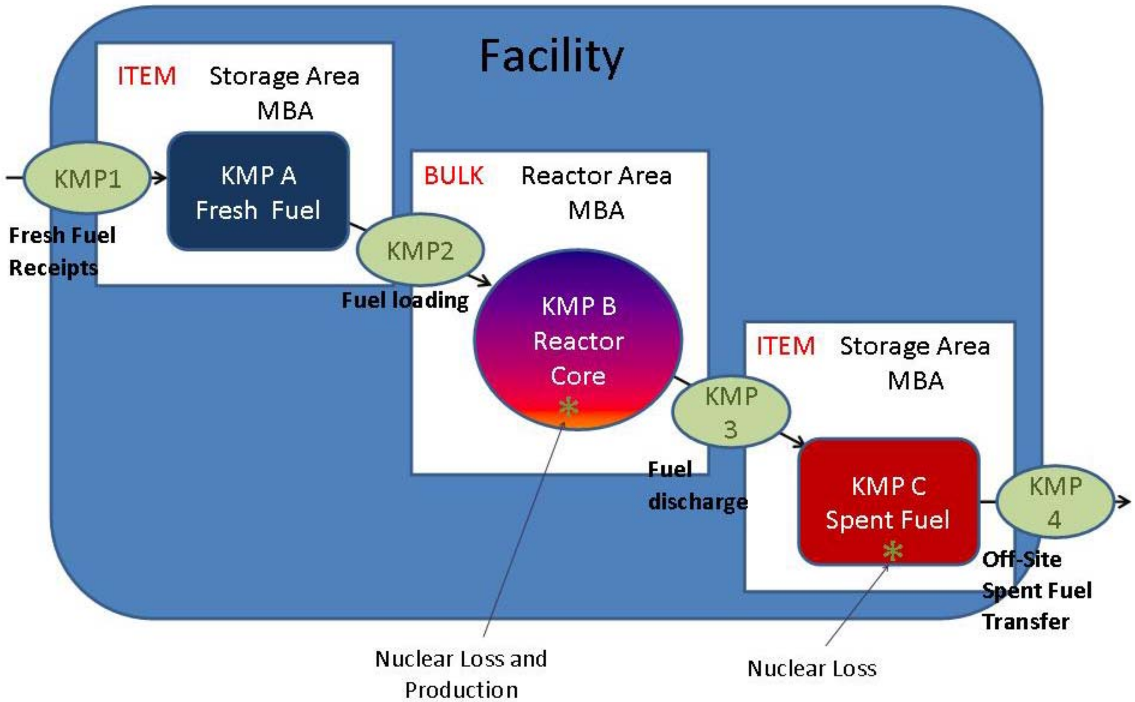

Figure 2. MBA structure for PBMRs using both bulk and item accounting

Safeguards Approaches at Molten-Salt Fueled Reactors

No plans for the production of a commercial MSFR exist at this time and this reactor type has been removed from consideration as a GEN-IV technology. However, this reactor design does demonstrate the extreme case where a reactor would have to be treated as a bulk handling facility. All safeguards measures at such a reactor would have to be analogous to those of a processing facility. Issues of MUF accrual and sigma-MUF would have be addressed during maintenance outages and treat those outages as clean-out activities.

Conclusions

Some reactor types produce safeguards challenges by making item accountancy difficult or impossible. With the global interest in nuclear power on the rise, it is likely that these or similar reactor types will become commonplace in the safeguards landscape. Now is the time to consider and develop robust safeguards approaches for these reactor types.

Some reactor types can be safeguards using traditional item accountancy with the deployment of new technologies. Some reactor types may require more innovative safeguards approaches to achieve the measurement goals in a robust and reliable fashion.

Still other reactor designs may require a completely new approach to reactor safeguards modeled on the bulk-facility approach.

If a safeguards approach relies strictly on maintenance of CoK, that approach needs to be both highly reliable and supported with CoK-recovery methodologies and/or reverification measurement approaches. As a result the reliance on CoK as a safeguards approach may prove to be more expensive than simply deploying new technologies to enable more traditional and robust safeguards approaches.

Development of reverification technologies relies heavily on modeling and simulation of various safeguards scenarios. To enable development of reverification technologies, improvements in spent fuel characterization and depletion codes are needed. Detailed reactor history data, and fresh fuel characterization data are needed, especially for MOX and GNEP fuels.

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