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CONTAINMENT AND SURVEILLANCE AS A PRIMARY APPROACH FOR SAFEGUARDING GEOLOGICAL REPOSITORIES

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ABSTRACT

The disposal of spent nuclear fuel in geological repositories presents an entirely new challenge for international nuclear safeguards, defying conventional safeguards approaches for other stages of the nuclear fuel cycle. Nuclear material accountancy (NMA), the primary mechanism by which safeguards are applied to detect and deter diversion for non-peaceful use, cannot apply to nuclear materials permanently removed from the active fuel cycle via disposal. Long-term safeguards for repositories fundamentally require containment and surveillance (C/S), and only C/S. We propose that a repository be designated a *Material Disposal Area* (MDA), which is distinct from a material balance area (MBA), as there is no "balancing" or verifying NMA for materials in an MDA. In handing off nuclear material from NMA-dependent safeguards, as applied to the active fuel cycle, to C/S-dependent safeguards, as applied to the MDA, the concept of a Transition is introduced. Transition begins after the last materials accountancy measurement, a partial defect verification (PDV), conducted before spent-fuel assemblies are encapsulated in disposal canisters. Transition ends when disposal canisters enter the repository MDA. During Transition, nuclear materials exist only as items, and safeguards assurance is primarily a matter of maintaining continuity of knowledge (CoK) on items and confirming their receipt and integrity at the repository MDA. During Transition, NMA is complementary to C/S, invoked only if CoK is lost and the suspect item does not enter the MDA and must be re-verified or returned. Once items have entered the MDA detailed NMA information is no longer needed for safeguards purposes.

INTRODUCTION

Conventional safeguards practice relies on nuclear material accountancy (NMA) complemented by containment and surveillance (C/S). This is a practical approach for nuclear materials that are accessible within the active fuel cycle. However, when this approach was developed little consideration was given to safeguards assurance for materials that were not accessible, and the approach breaks down for nuclear materials disposed in a deep geological repository. Such disposal facilities were not addressed in the 1960s and 1970s when the IAEA developed conventional safeguards (INFCIRC/66 and INFCIRC/153) [1], not only because no repositories existed at the time, but in large part because a common assumption was that valuable nuclear materials would not be disposed but recycled and remain in the active fuel cycle. National policies to dispose spent fuel without reprocessing and recycling gained favor in the 1980s and 1990s, and the IAEA began to consider safeguards approaches for such facilities, a task that continues today [2].

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The fundamental impediment to applying a conventional safeguards approach to nuclear material disposed in a geological repository is the practical inability to perform verification required to support NMA; that is, no periodic physical inventory taking (PIT) or its corresponding physical inventory verification (PIV) is possible on the disposed materials. But there is no a priori reason to require a universally applicable approach for nuclear material safeguards. Safeguards must adapt to basic material differences, as well as to different phases of the fuel cycle.

REPOSITORY CONTAINMENT

For safeguards purposes *containment* refers to "structural features of a facility, containers, or equipment [that are] used to establish the physical integrity of an area or items and can be used to maintain the continuity of knowledge (CoK) of the area or items by preventing undetected access to or movement of material, or interference with the items." [3] The geological formation or host rocks within a "restricted zone" forms the repository's containment. Two periods of concern for a repository are critical for containment. The first period includes the pre-operational and operational phases, when there will be open access between the surface and the underground workings (although only during the operational phase will there be nuclear materials at the facility). The second, indefinite period is the post-operational (or post-closure) phase when the facility has ceased operations and all access points have been closed and sealed shut.

In the case of a closed and sealed repository (post-closure phase), the only well-defined "structural feature" is the ground surface. By contrast, the host rock in which the repository is constructed provides only an ill-defined containment that has no sharply delineated boundaries and, therefore, cannot be monitored for penetration in the same way that, say, a door or other access through a well-defined structural feature can be monitored. The IAEA has therefore defined the "restricted zone" for a geological repository as "an area surrounding the repository in which no excavations are permitted." [4] Thus, the geological formation or host rocks within the restricted zone, as declared by the State, forms the repository's primary containment. The State must define the dimensions and boundaries of its repository's restricted zone (surface and subsurface), which must then be monitored to detect attempts to breach those declared boundaries.

During the pre-operational and operational phases, containment will include the same barriers as for the closed repository (post-operational phase); i.e., the ground surface plus the geologic formation (host rocks) within the State's declared restricted zone. However, in addition to monitoring for potential breach of the restricted zone, C/S measures during the pre-operational and operational phases will also include restrictions on and detection of movements of nuclear material into (and out of) declared access tunnels and shafts, as well as identifying undeclared activity or unreported access points. Successfully applying such measures require detailed design information verification (DIV), knowledge about all operational capabilities underground, as well as the ability to detect undeclared activities.

REPOSITORY END STATE

In developing a sustainable safeguards approach for nuclear materials permanently disposed in a mined geological repository, we start by considering the *End State*: the repository has ceased operations after having been filled to capacity; all tunnels, ventilation shafts, and other penetrations have been closed and backfilled; all access to underground areas has been closed off; any devices employed underground for safeguards purposes during the operational phase have been removed, or else disabled and abandoned. Thus, the End State describes the post-closure phase arbitrarily far into the future.

Ideally, a closed repository will impose minimal ongoing resource requirements for safeguards. Infrequent and random site visits, analyses of overhead satellite imagery, and possible monitoring of deployed seismic, acoustic, or other instruments will likely constitute the safeguards approach after repository closure. In this end state, no safeguards measures will apply to individual disposal canisters or to the spent fuel they contain. There is no access to the underground for any safeguards purpose. Safeguards assurance (no diversion to non-peaceful use or purposes unknown) comes entirely from two factors: (1) verifying the absence of attempts to access the repository, and (2) use of tools available to the IAEA to detect undeclared activities in a state with an Additional Protocol in force.

Repository safeguards as thus envisioned is a purely C/S approach: geological containment supplemented with surveillance by surface instruments and/or overhead sensing. The detailed repository inventory is inconsequential. C/S measures for the end state are not maintaining CoK for NMA. Instead, C/S measures for the end state are functioning for the purpose of intrusion detection (more akin to physical protection). The concept of a “C/S failure” is not relevant for end-state repository safeguards.

Our challenge is to connect this end state with safeguards as they are applied to the active nuclear fuel cycle, a stage we will refer to as “transition.” This transition is a critical aspect of the safeguards approach that we describe here, but first we introduce the concept of a *Material Disposal Area*.

NEW SAFEGUARDS DESIGNATION: MATERIAL DISPOSAL AREA (MDA)

To enable and formalize a satisfactory safeguards paradigm for disposal, we propose that a repository be designated as a *Material Disposal Area* or MDA. Unlike a material balance area (MBA), which is customary for NMA-based safeguards, an MDA would not call for establishing or maintaining any material balance. There is, after all, no associated physical inventory verification (PIV) for an MDA. However, since spent fuel disposed in a geological repository is not eligible for termination of safeguards, [5] an alternative characterization is needed. The MDA would call for a safeguards level of effort appropriate for disposed nuclear materials, one that reflects their inherent differences from nuclear materials in the active fuel cycle.

The MDA designation is consistent with the “black box” concept for geological repositories, as proposed by Fritzell and van der Meer. [6] The repository is recognized as establishing the repository’s restricted zone, which has a limited number of well-defined access portals. There is no need from a safeguards (or security) perspective to be concerned with the details of where materials are located in the underground complex, provided that access portals can be reliably monitored. The MDA takes the “black box” concept one step further. Not only are we assured that materials stay underground, but we recognize that there is no ongoing need to retain NMA information for the MDA.

A critical enabling concept for the safeguards approach proposed here is consent by the safeguards inspectorate(s) to release nuclear materials for disposal. The reader is reminded that nuclear materials already have other ways to exit safeguards accountancy. They can be consumed by nuclear processes in a reactor, they can decay, and they can become eligible for termination of safeguards when sufficiently diluted in process streams. The essential difference in geological disposal from those exit routes is that buried spent nuclear fuel could in principle still be used for nuclear explosives or weapons (if recovered). For this reason, safeguards are applied to geological repositories indefinitely. [4,5]

Nevertheless, the IAEA can decide *how* to apply safeguards to a geological repository. Under the safeguards approach proposed here, releasing nuclear materials for disposal would be to exit accountancy but not safeguards. A key aspect of how this is accomplished is by establishing the Transition MBA.

ALTERNATIVE SAFEGUARDS APPROACH: TRANSITION

Transition is the term we apply to the safeguards approach for handing off nuclear materials from the active fuel cycle to final disposal in the MDA. Materials in the active fuel cycle are subject to conventional NMA-based safeguards, whereas spent fuel encapsulated and emplaced in the geological repository MDA would be subject to C/S-only safeguards, as described above. In this section we focus on how the safeguards approach changes from material accountancy to item accountancy of assemblies and (then) disposal canisters, and finally to a repository MDA with no accountancy. Transition applies to most of the operations in an encapsulation plant, the transportation of canisters to the repository, and the receipt and emplacement operations at the repository (Fig. 1). The various steps are described in more detail below.

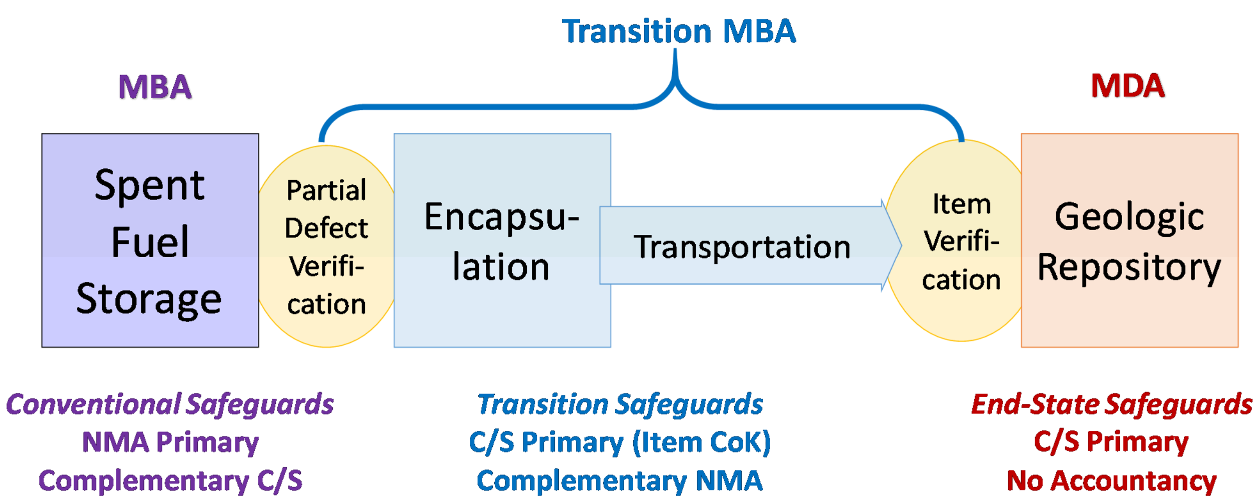

Figure 1. Illustration of the transition of safeguards approach from conventional MBA-based accountancy to MDA-based C/S for a disposal system having final storage co-located with encapsulation and a separate geologic repository requiring transport from encapsulation plant. Alternative systems might involve transportation to encapsulation after partial defect verification (PDV), but the essential requirements of the Transition MBA remain.

Partial defect verification: the accountancy exit portal

The last practical opportunity for an accountancy verification measurement is before spent fuel assemblies are aggregated into disposal canisters. The IAEA distinguishes between two broad categories of spent fuel assemblies: (1) those difficult to dismantle (e.g., welded fuel assemblies), and (2) those that can be dismantled. We assume the more stringent case, that of fuel assemblies that can be disassembled, and thus assume that before final disposal spent fuel assemblies need to be "verified with a partial defect test or… the best available method approved for inspection use." [7]. Verification consists of a nondestructive assay measurement of the spent fuel assembly, known as a partial defect verification (PDV), followed by a comparison of the measurement result with an operator declaration. Verification is accepted only if the IAEA deems that the PDV and the operator's declaration are consistent.

For transition safeguards, the final accountancy measurement for this partial defect test is accorded a safeguards role beyond its routine implementation in NMA. The measurement must also serve as an exit from the accountancy system for nuclear materials in the active fuel cycle. It is the *final* PDV. Note that consistency of declared values with measurement results is only one factor in the pass/fail decision. The next steps will depend on the result of the pass/fail decision (Table 1).

For any assemblies that are given a "fail" decision by the safeguards inspectorate, the facility operator could either (1) return the assembly to storage (i.e., still within the originating MBA), or (2) place that assembly in a separate holding area provided especially for rejected assemblies, pending resolution of the safeguards issue(s). In either case, the rejected fuel assembly does not enter the transition MBA. If PDV is successful (a pass), then the IAEA is acknowledging that there has been no material diversion, and the verified fuel assembly exits the storage MBA and enters the *transition* MBA.

Table 1. Matrix of decision outcomes and responsibilities for selected parties following possible PDV outcomes.

	Pass	Fail
Operator	Moves the spent fuel assembly into the encapsulation process	Aborts the encapsulation process for the failed spent fuel assembly pending resolution of the safeguards issue(s)
Safeguards inspectorate	Maintains CoK on the spent fuel assembly, both item identity and integrity, throughout the encapsulation process Retains NMA information for the spent fuel assembly, now in the Transition MBA	Informs the operator of the outcome and reason for "fail" decision Ensures that the spent fuel assembly does not proceed to encapsulation

All nuclear materials as items

Once past the accountancy exit portal, all nuclear materials in the Transition MBA are treated exclusively as items from a safeguards perspective. The items may be as intact spent fuel assemblies, closed boxes of fuel materials, or (eventually) disposal canisters. In transition, items are subject to C/S measures that maintain CoK on verified items through encapsulation, transportation and, finally, transfer to the repository MDA. The associated NMA information becomes an important *complementary* safeguards measure during transition. The primary safeguards approach in transition is to maintain item CoK (through C/S measures).

As long as CoK is not lost during transition, the NMA information will not be needed; nor will it be re-verified. There is no *a priori* reason (at least from a safeguards standpoint) to know anything further about item contents. If all items on which CoK has been maintained during transition verifiably and permanently enter the repository MDA, their contents must have enter the MDA as well and need no independent verification.

Encapsulation of spent fuel into disposal canisters

Most everything that takes place during the encapsulation process requires heavy shielding and remote handling within what we will call an encapsulation space. Verifying the physical design of the encapsulation space is critical for safeguards. The space cannot contain equipment that could be used to disassemble spent fuel assemblies, and there can be no unknown entrances or exits from the space that would permit a fuel assembly-sized object to be introduced or removed. Design verification should also establish the maximum number of assemblies the encapsulation space can accommodate and all locations within the space that assemblies could be gathered.

Within the encapsulation space, item identification might depend on being able to track assemblies and canisters during handling operations, which could be monitored with a combination of authenticated switches and sensors (position, motion, radiation). These are fundamentally C/S tools that support the primary safeguards approach. Exactly which tools are used and how they are applied will depend on developing a safeguards system tailored to the particular encapsulation process and physical facility design, presumably during the facility design phase (i.e., safeguards by design).

Transportation of canisters to the repository

Where a State's Encapsulation Plant and Geological Repository are not co-located, disposal canisters containing spent fuel would be loaded into shielded overpacks (transport casks) for transportation from the encapsulation plant to the repository. Overpacks could be sealed for safeguards item accountancy, assuring both item integrity and identification. Such an approach may obviate the need to tag the canister itself.

Safeguards assurance for canister transport entails two basic elements:

1) The integrity of every canister is maintained, and
2) Every canister is delivered to the underground repository.

These two elements are necessary and sufficient. If a canister reaches the repository intact, we would say that CoK has been maintained. Provided there has been no loss of CoK, detailed accountancy of canister contents provides no additional assurance. If CoK is lost because the integrity of the canister has been compromised, then only NMA can provide assurance that material had not been removed. In this way NMA is *complementary* to primary C/S during transition.

Table 2. Safeguards concerns and potential measures during transportation of canisters.

Safeguards concern	Relevant measure(s)
Integrity of the canisters is maintained at all times	Canister containment seal to assure no breach anywhere on the canister outer surface Second seal, using fundamentally different technology As required, video surveillance of the canister before seal is applied and after the seal final verification
Every canister leaving the encapsulation plant is delivered to the repository	Overpack seal Video surveillance at beginning and end of transport (before tag is applied, and after its final verification) Tracking of canister location

Item Verification: the MDA entrance portal

From a safeguards perspective, there needs to be a well-defined portal through which canisters enter the MDA. The portal might be established underground, within a central receiving area at the disposal depth; however, the approach could be modified to accommodate variations in repository designs, including the possibility of the portal being on the surface. Ideally, from a safeguards perspective, the portal should be as close as feasible to the final emplacement location for the canisters and be as close as possible to where a canister is removed from its transportation overpack.

At the repository MDA entrance portal, safeguards must establish the identity and integrity of each item (disposal canister). Just as for the final PDV at the entry to the Transition MBA, safeguards must render a pass/fail decision to the operator. If (and only if) "pass," then CoK has been maintained, and the canister can be removed from the transportation overpack (cask). The canister then passes through the MDA entrance portal for final disposal in the repository. Continuity of knowledge must be retained until the canister has passed the MDA portal. It is this step that officially constitutes "disposal," and the safeguards record of the item and its contents can be removed from the books.

Assuming there could be cases of "fail," there would need to be a nearby holding area where the problem canister(s), still in overpack, can be retained pending resolution of issues. Note that there could be other reasons (not related to safeguards) why the operator might need to abort canister disposal. Before returning a canister, however, the operator would need to coordinate with safeguards, since an inspectorate may need to inspect and/or replace seals before any further movement. A holding area facilitates matters so that disposal operations can proceed for accepted canisters.

Merely checking the receipt of arriving canisters is insufficient. Safeguards records would need to keep track of and allow periodic checks on the number of canisters within the transition MBA, specifically, those that have left the encapsulation plant. Such monitoring would alert the inspectorate about canisters that may be delayed or are otherwise unaccounted during shipment.

Thus, the repository portal is truly an entrance portal; that is, disposal canisters pass through in only one direction. Surveillance measures would be used to detect any exceptions or unexplained movements and should be capable of ensuring that overpacks are empty before leaving the facility.

Canisters in the repository

Within the operating repository, beyond verifying the design of the repository's underground complex, DIV must also assure that canisters cannot be opened underground. There is no need to maintain an inventory of materials within the repository, whether as canister items or as accountable material.

Table 3. Safeguards concerns and potential measures during receipt at repository MDA.

Safeguards concern	Relevant measure(s)
All canisters are delivered intact to the disposal locations underground,	Canister (overpack) seal/tag verification at the repository entrance portal Video surveillance for any process steps after item verification before passing through the repository entrance portal
The canisters are not opened underground, and	Design verification and random inspections to assure the absence underground of any equipment able to open canisters
No canisters are removed from the repository.	Portal monitoring of the access routes to the repository underground

Safeguards Accountancy Information

Not only is NMA difficult, if not impossible, to verify for materials in repositories, but that information should never again be needed, as the disposed materials will never re-enter the fuel cycle. If an assembly fails the final PDV, it does not enter the Transition MBA and remains under conventional NMA-based safeguards until the discrepancy or anomaly has been resolved, during which time NMA records are maintained on the nuclear material (the assembly) in question. For assemblies that do pass the final PDV, the IAEA accepts that there had been no diversion and those nuclear material (assemblies) enter the Transition MBA and proceed to disposal. NMA records are maintained (as complementary to C/S) while materials are in the Transition MBA until the final item accountancy when, if verified, each item (canister) exits the Transition MBA and enters the Repository MDA. Having served their purpose prior to disposal, that of validating what has been removed from the active fuel cycle, NMA records for materials in the MDA are no longer needed for safeguards purposes.

In fact, NMA is not merely unnecessary for materials in the MDA, NMA records may pose a risk from the standpoint of nuclear security. Material of well-documented accountancy is arguably more attractive to a potential proliferator than material without such characterization.

CONCLUSIONS

Conventional NMA-based safeguards on nuclear materials cannot be used for nuclear materials disposed in a geological repository. Annual verification of physical inventories in a geological repository is not possible. The key distinguishing concept for adopting an alternative safeguards approach is that the process is disposal, not long-term storage. Safeguards still apply; they are not terminated, but the safeguards approach must embrace the unique situation of permanent disposal in a geological repository. Several recommendations for a revised safeguards approach appropriate to this situation have been proposed in this paper.

The repository space for the final emplacement of nuclear materials should be designated as a Material Disposal Area (MDA) for safeguards purposes. The MDA designation distinguishes the repository and its function from a material balance area (MBA) used for conventional. safeguards. It is understood that nuclear materials are within the MDA, but qualitative and quantitative information (accountancy data) are not required for safeguards. Safeguards for an MDA rely on C/S measures only to ensure that the contents of the MDA remain in place and are undisturbed.

The Transition MBA comprises all activities after the final accountancy measurement (PDV) through entry into the MDA, during which CoK is maintained on items by using appropriate C/S measures. NMA records for items are only needed if CoK has been lost. The transition from conventional NMA-based safeguards to C/S-based safeguards for materials disposed in a repository is accomplished by using C/S measures for item accountancy as the primary safeguards measure, with NMA serving as a complementary measure.

There is no fundamental need to maintain detailed accountancy records for items after disposal. Once nuclear material has been disposed; i.e., a canister has been delivered into the repository MDA, transition is over and there is no further need for safeguards to maintain the associated NMA records for the contents of the disposed canister.

The safeguards approach proposed here relies on C/S measures to ensure that disposed materials remain out of any active nuclear fuel cycle, which complements other tools available to safeguards with an Additional Protocol for the detection of undeclared activities. The unique nature of a geological repository demands a novel approach to safeguards. The approach proposed here could meet that demand.

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