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Containment & Surveillance and Canister ID Applied to the Final Disposal of Spent Nuclear Fuel

Robert J. Finch[1], Dina Chernikova[2], Heidi A. Smartt[1], Lars Hildingsson[3], Risa Haddal[1]

[1]Sandia National Laboratories, Albuquerque, NM, USA
[2]Swedish Research Council, Stockholm, Sweden
[3]Swedish Radiation Safety Authority, Stockholm, Sweden.

rfinch@sandia.gov

ABSTRACT

The International Atomic Energy Agency's expert group on Application of Safeguards to Repositories (IAEA/ASTOR) recently summarized the group's work from 2011 to 2016, including a review of technologies for containment and surveillance (C/S) applied to geological repositories for disposing spent nuclear fuel and other accountable nuclear materials (IAEA-STR-384). The report also includes potential C/S measures for encapsulation plants as well as for transporting spent fuel. This paper describes those technologies and C/S measures, as well as technologies being developed for uniquely identifying disposal canisters (canister ID).

Permanent disposal of spent fuel presents a major new approach for international safeguards, as reverifying the final accountancy measurement of a spent-fuel assembly is not feasible after the fuel assembly has been emplaced and the repository closed. This results in an unprecedented reliance on maintaining continuity of knowledge (CoK) through effective C/S measures: from final accountancy through encapsulation, transportation and final disposal. Here we review C/S measures described in the 2017 IAEA/ASTOR Group report. The role of C/S for repositories is to maintain continuity of knowledge (CoK) on spent fuel (or other nuclear material under safeguards) following the final safeguards accountancy measurement through final disposal; that is, emplacement underground and final repository closure. Such C/S measures must include, not only repositories, but encapsulation plants and spent-fuel transportation, as these constitute a significant challenge to confidently maintaining CoK.

Introduction

This IAEA published a special technical report in 2017 on Technologies Potentially Useful for Safeguarding Geological Repositories,[1] which summarized work performed from 2011 to 2016 by the IAEA expert group on Application of Safeguards to Geological Repositories (ASTOR). That report includes contributions from five focus groups: Design Information Verification, Non-Destructive Assay Verification, Containment and Surveillance, Satellite Imagery & Geophysical Techniques, and Long-Term Data Management. This paper summarizes the contribution to that report by the Containment and Surveillance focus group.

We describe possible containment and surveillance (C/S) measures for geological repositories including encapsulation plants as well as potential C/S measures applicable to the transportation of spent nuclear fuel. We conclude with promising technologies for uniquely identifying disposal canisters (canister ID).

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The overarching role of C/S for repositories is to maintain continuity of knowledge (CoK) on spent fuel (or other nuclear material under safeguards) following the final safeguards accountancy measurement through final disposal. Because these constitute a significant challenge to confidently maintaining CoK, C/S measures for transportation and encapsulation plants must be considered in addition to those to be applied at a repository. Once spent fuel is transferred into the geological repository for emplacement, C/S and monitoring measures will be the only safeguards tools capable of maintaining CoK on a repository's contents.

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 (CoK) of the area or items by preventing undetected access to or movement of material, or interference with the items."[2] The geological formation or host rocks within a "restricted zone" forms a 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 a 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."[3] Thus, the geological formation or host rocks within the restricted zone, as declared by the State, forms a 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 detecting 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.

Continuity of Knowledge (CoK)

CoK has been defined as uninterrupted and authentic data or information about nuclear material that provide the IAEA with adequate insight to draw definitive conclusions that nuclear material is not being diverted from peaceful purposes.[4] Thus, CoK can be viewed as an outcome, not a process, and that CoK must first be attained – and then maintained – to provide confidence that the knowledge can be used to draw valid safeguards conclusions. The following sections describe CoK as it applies to transportation, encapsulation and disposal.

1. Continuity of knowledge for an encapsulation plant

Encapsulation plants are an integral part of maintaining continuity of knowledge on fuel after the final accountancy measurement for safeguards. It is during encapsulation that the IAEA has its last opportunity to observe fuel assemblies before they are put into disposal canisters. While this is a critical juncture in the disposal process, C/S measures to be applied at an encapsulation plant are, for the most part, likely to be more-or-less standard C/S equipment, such as radiation monitors and surveillance cameras (which will need to be radiation resistant and redundantly deployed if used inside a handling hot cell).

2. Continuity of knowledge during transportation

Transporting spent fuel, whether as assemblies or in disposal canisters, is a crucial link between the final accountancy measurement for safeguards and final disposal. The near impossibility of re-verifying fuel assemblies after their final partial defect measurement, especially once encapsulated inside disposal canisters, necessitates maintaining continuity of knowledge with an unprecedented high level of confidence. Dual, independent seals may need to be applied to transportation casks. Although not currently practiced, seals on transport casks will almost certainly need to be both applied and removed by the operator, as the application and removal of seals will be a continuous process occurring on a regular basis, possibly daily. Additional C/S measures that could be applied while transporting disposal canisters might include surveillance cameras (on board ships or trucks), radiation detectors (e.g., a mobile unit neutron detector or MUND), and geolocation with data transmission and authentication. Potential security concerns with location monitoring would need to be accommodated.

3. Continuity of knowledge for a geological repository

Spent fuel disposal canisters delivered in transport casks from an encapsulation plant will be taken to the repository's receiving and buffer storage area. Before emplacement in a repository, disposal canisters may stay in buffer storage for some period, during which C/S measures will be applied at the buffer-storage area; transportation casks might remain intact during this period. If disposal canisters are to be removed from transport casks before being placed into buffer storage, seals on transport casks would be removed (after being verified) and dual C/S measures[5] would be applied to ensure no diversion can go undetected before disposal canisters are emplaced underground. Cameras and radiation monitors would be used to detect movements of transport casks and/or disposal canisters in the buffer-storage area, and seals might be applied to enclosures, if available. Access points to the repository during the operational phase will need to be monitored for potential diversion attempts. Applicable C/S measures at access points include radiation detectors (possibly paired directional detectors) to ensure no fuel can be returned undetected to the surface via such access points.

Recognized challenges for maintaining CoK at a repository include adequately detecting radiation through shielded casks and through mined rock debris that might be used to hide disposal canisters, especially given weaker radiation emitted by fuel after long cooling times, as well as potential interference from ambient background radiation or natural radiation emitted by rock debris. Other C/S measures that might be applied at a repository include cameras (visual and, potentially, thermal infrared), mass measurements at entry and exit points (to help detect the presence or absence of a massive disposal canister), ultrasound measurements (to distinguish loaded casks or canister transporters from empty ones), and laser scanning (for monitoring movements and shapes). No single monitoring method or measurement would suffice to provide unambiguous detection of possible diversion attempts (or the lack thereof). Thus, multiple, independent C/S measures are recommended for every access point, with details of how each access point is used and designed factoring in to the choice of C/S measures.

Seals

Seals could be used for certain storage and holding areas at an encapsulation plant or a repository during operations, and would likely be applied to transportation casks during transport. A seal is a tamper-indicating device (TID) used to detect unauthorized access to materials and other items within secured enclosures (containment). A sealing system includes (1) the seal itself, (2) a way to apply the seal (e.g., metal wire, optic cable) and (3) the containment enclosing the nuclear material (NM) or other protected items.[6] All three components must be examined to verify that a sealing system has not been tampered with. Seals also uniquely identify secured containers to which they are attached and are authenticated by confirming that identity. Seals do not provide physical protection of a sealed item but are designed to give evidence of possible manipulations. We distinguish here between two broad types of seal. Passive seals do not require an energy source; whereas active require power to operate.

1. Passive sealing systems

Passive sealing systems require no power to operate. The integrity of passive sealing systems must be verified in the field or during a subsequent analysis after a seal has been removed. Several types of passive seals are used by the IAEA for a variety of applications (Table 1).

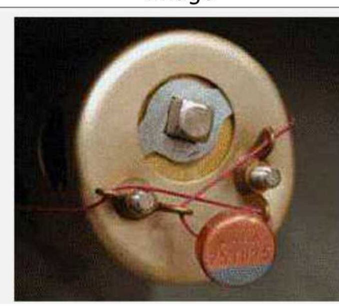
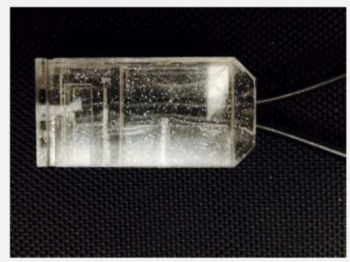
Table 1. Passive Sealing Systems	*Description*	*Image*
Metal seal (CAPS)	Single-use seal Metal wire loop seal CAPS is used extensively by IAEA Verified after removal	
Glass seal	Single-use seal Metal wire loop Same applications as for CAPS Seal body fragments when tampered Currently being tested	

Table 1. Passive Sealing Systems	*Description*	*Image*
Ceramic seal	Single-use seal Metal wire loop Same applications as for CAPS Metal wire loop seal Body fragments when tampered Under development	
Adhesive seal (VOID)	Adhesive seal For short-term applications (24 hours or less). Seal degrades or deforms when detached or reattached	No image available
Passive Fiber-Optic Sealing system (FBOS)	Fiber-optic loop seal COBRA V uses FBOS technology plus reflective particle tags molded into the polycarbonate body for unique ID Cut loop produces a unique random pattern of uncut fibers that can be verified by recording an image of the pattern made by the fiber ends verification assembly records a reference image of the seal's uncut-fiber pattern	
Ultrasonic Optical Sealing Bolt (UOSB) and Ultrasonic Sealing System Bolt (USSB)	used to seal the lids of containers with spent fuel assemblies UOSB is primarily used for underwater applications USSB commonly used for dry-storage casks ultrasonically verifiable replaces one standard bolt on a container lid random pattern of metal discs plus a frangible element that breaks during attempted removal USSB is effective for sealing shipment and storage containers of LWR spent fuel assemblies, and might be promising for sealing transportation casks containing spent fuel assemblies or disposal canisters (UOSB shown)l	

2. Active sealing systems

Active sealing systems require a power source to operate. Active sealing systems continuously monitor seal integrity and record opening, closing, and tampering events. Data can be retrieved during an inspection or may be transmitted to allow the seal to be remotely monitored. Several active sealing systems are presented in Table 2.

Table 2. Active sealing systems	*Description*	*Image*
Active Fiber-Optic Seal (EOSS)	reusable seal consisting of a fiber-optic loop and an electronic seal high reliability, long-duration surveillance in applications that require periodic access Laser pulses continuously monitor the loop for indications of opening or tampering, and every instance that the seal is opened or closed is stored in the seal's memory. time, date and duration of opening and closing the fiber-optic loop are recorded internally A dedicated reader (e.g. a laptop with EOSS verification software) is used to verify the seal up to 32 EOSS seals may be daisy chained, allowing all seals to be connected in sequence through a single connection	
Remotely Monitored Sealing Array (RMSA)	sealing system configured in a network for multiple items	
Laser Mapping system for Containment Verification (LMCV)	laser scan of a container's surface interferometric calculations generate a 3-D image that maps unique surface variations image is compared with reference image to demonstrate that a container has not been tampered with (e.g., cut and rewelded).	

Surveillance Systems

A variety of surveillance systems are in use by IAEA, the most common being video cameras, the most recent being the IAEA's Next Generation Surveillance System (NGSS), which is due to replace earlier systems by 2020. Table 3 lists two other surveillance systems, the Laser Surveillance System (LASSY) and an Infrared (IR) camera; the latter being untested for safeguards applications. Such surveillance systems could be used in encapsulation plants and surface facilities at geological repositories (radiation-hardened cameras would be required for spent fuel handling cells at an encapsulation plant).

Table 3 Surveillance Systems	*Description*	*Image*
Next Generation Surveillance System (NGSS)	Video surveillance (optical camera) modular and scalable optical surveillance system records visual evidence of events with a front-end camera, processing and storing data locally, or data can be forwarded to a data-consolidator unit where data are stored and then forwarded via a remote monitoring connection (where allowed) scalable to any number of cameras Advanced security features, low power consumption, and solid-state storage media Each NGSS camera can record up to four fields of view simultaneously	
Infrared (IR) camera	Thermal images based on an object's temperature Displays colors correlated to IR intensities emitted by object not currently used for IAEA safeguards	No image available
Laser Surveillance System (LASSY)	Surveillance system based on one or several 2-D Laser-distance sensors Two analyzers provide 'zone-monitoring' and 'containment-monitoring' Detection can trigger a surveillance camera (optical or IR) Originally used for monitoring spent fuel storage pools	No image available

Unattended Monitoring Systems and the Mobile Unit for Neutron Detection (MUND)

Unattended monitoring systems (UMSs) operate around the clock all year without requiring an inspector to be present. Several families of UMSs can be distinguished, according to the technology upon which they are based.[6] Of particular interest for monitoring spent-fuel assemblies and disposal canisters is the mobile unit for neutron detection (MUND). Because detecting low levels of gamma-radiation emitted from a disposal canister and its shielded transportation cask can be challenging, neutron detection is likely to be most appropriate method for monitoring spent fuel disposal canisters and transportation casks. The MUND is an all-in-one neutron-detection system for data collection and storage that can run on battery power. Each unit has a ^{3}He detector mounted inside a polyethylene moderator slab; it is integrated with supporting electronics inside a single sealable enclosure. Once installed, a MUND unit is typically serviced by replacing it with a fully recharged unit. A MUND collects data for more than eight weeks without service.

Surveillance and Radiation Detection Review Tools

1. General Advanced Review Station Software (GARS).

Surveillance images are evaluated by inspectors using the General Advanced Review Station Software (GARS). This software was developed to run on a personal computer with the appropriate media drives to review the recorded images from all DCM 14 based systems. GARS has been further developed to enable the review of surveillance records generated by the Next Generation surveillance System (NGSS). At its simplest, GARS provides a flexible and user-friendly inspector interface (similar to popular commercial media players) for the review of images and data from flashcards, removable hard drives, CD-ROMs and digital linear tapes. GARS also has advanced features that can be used to reduce an inspector's review effort, including image and data decryption and authentication, scene-change detection, enhanced digital images, and multiple camera-display options. GARS can run on a personal computer equipped with the appropriate digital media peripherals. And is used to review surveillance systems that will be replaced by the NGSS.

2. Integrated Review and Analysis Package (iRAP)

The integrated Review and Analysis Package (iRAP) is a modular software package developed by EURATOM as the successor to CRISP (Central RADAR5 Inspection Support Package). iRAP has long been used by EURATOM inspectors and was recently adopted by the IAEA as a future review tool. EURATOM and IAEA have agreed to jointly develop iRAP as an 'all-in-one review platform.[7] The iRAP software package meets current requirements; however, in addition to enhancing technical measures and efficient use of resources, plans for geological repositories and encapsulation plants in Sweden and Finland have motivated EURATOM and the IAEA to adjust existing methodologies to prepare for future challenges.

Disposal Canister Identification

Canister identification might be used to maintain CoK on individual disposal canisters. Although no specific method for labelling disposal canisters has been proposed by a State operator, engraving or marking a canister's outer surface could damage a canister's integrity and hamper long-term safety performance, as such markings could induce corrosion. methods that mark an interior surface or placing a unique tag inside a canister have been proposed (Table 4). In addition, a unique identification must be difficult to falsify, counterfeit, or duplicate. Towards this end, measuring and recording intrinsic attributes, such as canister weight, radiation profile, temperature, or other characteristic properties, could prove useful and difficult to falsify. On the other hand, several of these properties might prove difficult to use (e.g., weight, radiation, temperature), as a State operator is likely to load most canisters with the goal of optimizing many such properties, notably thermal power and criticality, whereby such properties could be closely similar among different canisters. A few other intrinsic properties have been proposed as potential unique IDs, including the micro-structure of a canister's surface, eddy current response, and ultrasonic response, but most of these have not been proven effective. Three ID methods under development are described in Table 4.

Table 4. **Canister Identification**	***Reflective Particle Tag (RPT)***	***Ultrasonic ID for Copper Canisters***	***Tungsten-Based Identifiers***
Technology description	field-applied tag composed of specular hematite particles randomly dispersed in a clear, adhesive polymer matrix	chamfers milled on the canister lid's inner surface before closure are read by an ultrasonic transducer while rotating about the lid's circumference.	A tungsten insert, with a hole pattern based on a binary code, is placed between the cast-iron lid and the copper lid of a Cu canister. Selectively collimated gamma rays reveal a unique tag pattern as recorded by a gamma detector.
Technology readiness level (TRL)	4-5 (prototype)	4 (lab demo)	4 (lab demo)
Technical limitations	Uncertain reliability over a repository's operational timeframe	Reading takes ~5 minutes per canister (expected); requires acoustic-coupling medium (e.g., water)	Gamma signal weakens over time, increasing measurement time.
Estimated costs	Unknown	€20 000 (estimated for two scanning systems: EP* & GR*)	Unknown
Sustainability, standardization, supply chain	Unknown	Standard COTS* hardware	Standard COTS* hardware used to read insert
Ease of use/Level of operator skill/Major infrastructure needs	Easy to use Low skill level required	Standard inspector skills	Standard inspector skills plus training in the use of COTS reader equipment (e.g. gamma camera)
Methods of data validation/authentication	Dedicated reader system	Ultrasonic authentication signature combined with random Cu flow generated during welding	
Expected 'Alarm' rates	Unknown (expected to be low)	Zero	Unknown
Uniqueness against duplication/falsification			Potentially low could combine with other 'intrinsic' characteristics

* EP: encapsulation plant; GR: geological repository; COTS: commercial off-the-shelf

SUMMARY

Permanent disposal of spent fuel will require unprecedented reliance on CoK on spent fuel assemblies through highly effective C/S measures, from final accountancy through encapsulation, transportation and final disposal. Maintaining CoK on spent fuel (or other nuclear wastes under safeguards) following the final safeguards accountancy measurement through final disposal must include, not only repositories, but encapsulation plants and spent-fuel transportation, as these constitute a significant challenge to confidently maintaining CoK. The variety of C/S technologies potentially useful for safeguarding geological repositories and encapsulation plants that we have reviewed here are described in more detail in the 2017 IAEA/ASTOR Group report,[1] and include both well-established and several novel technologies.

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[5] Dual C/S employs at least two independent methods for assuring continuity of knowledge whereby both measures must verify positively to be able to conclude that continuity of knowledge has been maintained. If either one should verify negatively, continuity of knowledge has been lost.

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