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Maintaining Continuity of Knowledge on Nuclear Waste Destined for Geological Repositories. A Case Study of Plutonium Shipments to the Waste Isolation Pilot Plant (WIPP)

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ABSTRACT

This study examines methods that can help maximize confidence in maintaining Continuity of Knowledge (CoK) on plutonium-bearing wastes, from a final safeguards-verification measurement through emplacement underground. The study identifies Containment and Surveillance (C/S) measures that can be applied during packaging of plutonium wastes at the Savannah River Site (SRS) in South Carolina, USA, through shipment to, and receipt and disposal at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico, USA. Results of this study could apply to countries with a Comprehensive Safeguards Agreement (CSA) that plan to dispose in a geological repository plutonium or other non-fuel nuclear materials that are under international safeguards.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
AP	Additional Protocol
ASTOR	Application of Safeguards to Repositories (IAEA expert group)
CCP	Central Characterization Program
CL	Closure Lid
CoK	Continuity of Knowledge
C/S	Containment and Surveillance
CSA	Comprehensive Safeguards Agreement
CH	Contact-Handled
DIV	Design Information Verification
DOE	Department of Energy
DOE/EM	Office of Environmental Management
HEU	High-Enriched Uranium
HRCQ	Highway Route Control Quantity
ICV	Inner Containment Vessel
IAEA	International Atomic Energy Agency
MUF	Material Unaccounted For
NDA	Non-Destructive Assay
NM	Nuclear Materials
NNSA	National Nuclear Security Administration
OCA	Outer Containment Assembly
PATCDs	Payload Assembly Transport Certification Documents
PCTCDs	Payload Container Transport Documents
RCT	Radiation Control Technician
RQ	Reportable Quantity
SAGOR	Spent Fuel in Geological Repositories (IAEA expert group)
Sandia	Sandia National Laboratories
SNF	Spent Nuclear Fuel
SRNL	Savanah River National Laboratory
SRS	Savannah River Site
SWB	Standard Waste Boxes
TCO	Transportation Certification Official
TDOPs	Ten-Drum Overpacks
TRU	Transuranic

Abbreviation	Definition
USEPA	Uniform Hazardous Waste Manifest
WCO	Waste Certification Official
WDS	Waste Data System
WIPP	Waste Isolation Pilot Plant
WWIS	WIPP Waste Information System

1. PROJECT OVERVIEW

1.1. Goals and objectives

This study examines methods that can help maximize confidence in maintaining Continuity of Knowledge (CoK) on plutonium-bearing wastes, from a final safeguards-verification measurement through emplacement underground, by identifying Containment and Surveillance (C/S) measures that can be applied during packaging of plutonium wastes at the Savannah River Site (SRS) in South Carolina, USA, through shipment to, and receipt and disposal at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico, USA. Results of this study could apply to countries with a Comprehensive Safeguards Agreement (CSA) that plan to dispose in a geological repository plutonium or other non-fuel nuclear materials that are under international safeguards.

The objective of international safeguards is to deter the spread of nuclear weapons through early detection of misuse of nuclear materials or technology [1, 2].[1] Permanent disposal of SNF and other Nuclear Materials (NM) in deep geological repositories, while widely regarded as a safe means of nuclear-waste management, presents new safeguards challenges. Standards for repository safeguards set forth by the International Atomic Energy Agency (IAEA) include maintaining CoK on SNF and waste NM from the final safeguards accountancy measurement, through waste transport, waste receipt, emplacement, and for as long as a State's safeguards agreement with the IAEA remains in force. Methods for maintaining CoK during transport of waste NM have not been developed, thereby creating a potential gap in CoK approaches and technologies.

For this study, the team identified a unique opportunity to explore technically credible approaches for maintaining CoK on waste materials shipped to and disposed at the WIPP. WIPP is a deep geological repository for the permanent disposal of transuranic (TRU) waste. Shipments of TRU-bearing wastes to WIPP can provide information and insight into effective measures for maintaining CoK on accountable NM destined for disposal in other countries. Results of this study may assist in reducing material-accountancy and inspection burdens on facility operators subject to international safeguards, and on IAEA inspectors.

1.2. Collaborative engagement with stakeholders

This study explored feasible methods, and identified possible gaps in existing methods, for maintaining CoK on waste shipments destined for WIPP. Sandia National Laboratories (Sandia) conducted this study in collaboration with U.S. stakeholders including the WIPP facility, the U.S. Department of Energy's National Nuclear Security Administration (DOE/NNSA/NA-241), Office of Environmental Management (DOE/EM), Savannah River National Laboratory (SRNL), Savannah River Site (SRS), and Consolidated Nuclear Security (CNS) LLC. We examined and analyzed packaging, sealing, transportation, receipt, and emplacement operations for selected waste materials shipped from SRS to WIPP, as well as promising C/S technologies and monitoring capabilities relevant to international safeguards. This study focused on shipments of non-pit plutonium waste from SRS to WIPP [3] and comprises the following objectives to

[1] The primary goal of international safeguards is to prevent diversion of nuclear materials from peaceful uses by the state, which differs from domestic safeguards that are implemented by a state to protect against theft or sabotage of materials by non-state actors.

maintain CoK on the wastes during shipment and disposal, and to potentially ease the burden on disposal-facility operators and IAEA inspectors in countries with CSA's in force.

During this study, we performed the following:

- Consulted with stakeholders to define criteria for packaging, transport, receipt, and emplacement operations in the repository.
- Examined CoK requirements and identified appropriate C/S measures.
- Developed recommendations for maintaining CoK on wastes during packaging, shipment, receipt, and emplacement.
- Identified options and requirements for terminating safeguards on Pu-bearing wastes.

In examining CoK requirements and appropriate C/S measures, the primary focus was on ensuring wastes are disposed as declared and that any undeclared removal of waste would be detected with a high degree of confidence. We also evaluated options and requirements for terminating international safeguards on accountable nuclear materials declared as waste; that is, waste material that will no longer be subject to international safeguards after it has been 1) consumed, 2) diluted so that it is no longer useful for nuclear activities subject to safeguards, or 3) declared to be "practicably irrecoverable" [4].

Findings and recommendations are reported in three key areas:

- Safeguard approaches for maintaining CoK on waste destined for disposal in a geological repository;
- C/S and, where applicable, dual C/S measures for maintaining CoK during transport of wastes and ensuring confidence that wastes are emplaced as declared; and
- Requirements and options for terminating international safeguards on plutonium-bearing wastes.

Recommendations and conclusions drawn from this study may provide the IAEA with an informed approach to maintaining CoK on shipment, receipt, and emplacement of waste NM at geological repositories under international safeguards.

2. BACKGROUND AND CONTEXT

In the mid-1980s, the IAEA began to consider appropriate safeguards for wastes proposed for disposal as measured discards and SNF to be emplaced in geological repositories. That work focused (and continues to focus) on developing safeguards approaches for the permanent disposal of SNF [see Appendix A.1]. Safeguards approaches for separated plutonium have been largely unexamined by the IAEA. Nevertheless, some States with CSAs in force do possess separated plutonium that might be declared as waste for permanent disposal in a geological repository. Material differences between SNF and separated plutonium mean that safeguards approaches applied to SNF cannot be uniformly applied to separated plutonium; however, while IAEA policies outlined below apply strictly to the encapsulation, transport and geological disposal of SNF, similar approaches are likely to apply to other nuclear materials declared as waste, including plutonium. Appendix A.4 provides a more detailed discussion of material differences between SNF and separated plutonium and potential impacts on safeguards approaches, but first we briefly outline key safeguards approaches recommended by the IAEA for the encapsulation, transport and geological disposal of SNF, indicating how these approaches can apply to safeguarding separated plutonium-bearing waste for disposal.

3. GEOLOGICAL REPOSITORY SAFEGUARDS: IAEA POLICIES AND PROCEDURES

IAEA policy states that the safeguards approach for a geological repository should be based on the following criteria. [5]

1. Verify design information during design, construction, and operation
   a. Detect differences between declared facility designs and declared design information (based on the design information questionnaire for the facility)
2. Verify receipts and flows of nuclear materials
   a. Verify receipt of waste canisters (or drums in the case of WIPP) in shipping casks at the repository's receiving area;
   b. Verify the continued presence of waste canisters in the repository's storage area;
   c. Verify the declared transfer of waste canisters into the repository;
   d. Verify that no waste canister (or its contents) is removed undeclared from the repository
   e. Detect undeclared excavation activities that could result in accessing emplaced wastes
3. Verify nuclear material contents of incoming waste containers; and
   a. Detect replacement of waste material with dummy material at the gross defect level (e.g., a waste drum),
   b. Detect removal or replacement of waste material from a waste container at the partial or bias defect level;
   c. Verify that selected measured signatures are consistent with the simulated signatures calculated from declared information for the waste (e.g., gross gamma intensity, gamma radiation from specific isotopes, total neutron count rate, and neutron multiplication),
4. Maintaining CoK of the nuclear material inventory.
   a. Detect tampering of waste containers (e.g., waste drums or shipping casks)
   b. Detect removal of waste from shipping containers or waste drums

The IAEA's verification requirements are designed to provide assurance that no nuclear material is diverted for non-peaceful uses. The IAEA requires spent fuel be verified at the gross-defect level if the spent fuel, such as welded assemblies, cannot be dismantled without leaving readily observable indicators. The IAEA requires a partial or bias defect measurement for those assemblies that could be disassembled without leaving readily observable indicators. This latter situation might apply to waste drums containing plutonium wastes.

C/S measures are applied to wastes after the final safeguards accountancy measurement from the time of the measurement until receipt and disposal at the repository. This would include maintaining CoK on verified plutonium wastes if the final safeguards accountancy measurement is performed at the SRS. If C/S measures are evaluated as being successful, CoK will have been maintained from the waste-verification until receipt at the repository, and the waste may not need to be re-measured.

The IAEA requires that C/S measures meeting dual C/S criteria[8] be applied to nuclear material placed into difficult-to-access locations (e.g., disposal canister or emplaced underground) after the final safeguards accountancy measurement. As noted above, if the applied dual C/S measures are evaluated as being successful, the previously verified nuclear material does not have to be re-measured. For example, spent fuel that has been verified by the IAEA at a reactor and placed into a cask that is kept under dual C/S would not need to be reverified at an encapsulation facility.

Although current IAEA policy refers explicitly to SNF, similar criteria can be applied to all accountable nuclear materials declared as waste; that is, waste nuclear materials that remain subject to IAEA safeguards. Once safeguarded waste has been emplaced underground in a repository, it cannot be re-verified (i.e., waste emplaced underground cannot be reverified because it is in a difficult-to-access location). This places a high reliance on C/S measures to maintain CoK on the waste after emplacement, and the IAEA requires C/S measures for the repository meet the requirements of dual C/S.

If C/S measures applied during packaging and shipment of waste cannot be evaluated as having been successful, CoK is lost on those wastes and they need to be reverified. If this occurs, waste could be re-verified at the WIPP receiving area. The waste in question would need to be set aside (under surveillance and/or seal) until the IAEA can re-verify the waste before it is emplaced in the repository. Because the possibility exists for waste to be re-verified, it is unlikely that dual C/S measures will be necessary for shipping containers during transportation from SRS to WIPP.

The focus of this report is on bullets 3 and 4 above; that is, maintaining CoK on wastes after they have been verified. For further detail on the IAEA's development of geological repository safeguards policies and procedures, see Appendices A.2 and A.3.

4. WIPP CRITERIA AND PROCEDURES FOR WASTE PACKAGING, TRANSPORT, RECEIPT, AND EMPLACEMENT

The WIPP maintains specific criteria for waste packaging, transport, receipt and emplacement. These criteria focus on technical requirements for the assembly, certification, shipment, and unloading of contact-handled (CH) packages which consist of TRU package transporter shipping containers, or TRUPACTs (Figure 1). These procedures help us define potential C/S approaches for waste NM.

Figure 1. TRUPACT-II shipping containers (three TRUPACT-II are shown on a transportation vehicle)[2]

4.1. Packaging

Containment and surveillance measures should provide a high level of assurance that waste to be packaged for transport and disposal are placed into the designated disposal container (drum) and that each filled drum is placed as declared into its designated shipping container. According to WIPP, technical requirements and instructions for the assembly of a Central Characterization Program (CCP) payload for CH packaging [6], 55-gallon waste drums, Standard Waste Boxes (SWBs), or Ten-Drum Overpacks (TDOPs; Figure 2) destined for WIPP are loaded into TRUPACT-II shipping containers. The TRUPACT II is designed to transport up to 14 55-gallon drums, two SWBs or one TDOP [7]. The WIPP packaging procedures refer primarily to the processes required for preparing SWB and TDOP payloads.

Figure 2. Ten Drum Overpack (TDOP)[3]

[2] Source: wipp.energy.gov
[3] Ibid.

The plutonium waste to be shipped to WIPP is incorporated into a waste form that will be packaged in 55-gallon waste drums. Plutonium wastes will be conditioned before being placed into waste drums by "downblending" the plutonium in a waste matrix [8, p. 17]. The composition or physical form of the resulting waste form is not available.

For packaging 55-gallon drums into TDOPs, approximately 15 steps are required before closing and sealing the TDOP overpack for shipment [6]. For loading SWBs into TDOPs, the first three steps include, 1) removing each SWB lid, 2) inspecting the SWB to account for any damage or defects and to perform any needed maintenance (for safety purposes), and 3) verify waste drum numbers for identification. Once these initial steps are complete, waste drums are moved from the storage area to the payload assembly area (step 4) where the drums are checked for tags, lid integrity, and inspection reports (steps 5-8). It should be noted that the packaging procedures [6] used at SRS do not require material verification of the content of waste NM in the drums. This is a key difference between IAEA and WIPP procedures for preparing and shipping waste destined for a geological repository.

Once the drums are inspected for integrity, a Radiation Control Technician (RCT) initially prepares the waste payload at the host site (in this case, SRS) by performing radiation and contamination surveys of the payload assembly. After completing and recording these surveys, a CCP Waste Certification Official (WCO) selects waste drums to be packaged by using the WIPP Waste Information System/Waste Data System (WWIS/WDS); the heaviest waste drums are placed on the bottom row of each TDOP. After selecting the payload containers, information about each drum is entered into the WWIS/WDS for overpack container certification. Next, waste drums are inspected for damage or defective parts or components that could negatively impact containment integrity of a transportation overpack. After completing the safety inspection and verifying and recording the ID for each waste drum, drums are transferred into SWBs (if applicable). Labels are applied to the flat sides of each SWB; each label has information about radiation and contamination surveys, dose rates, and the type of waste. A Transportation Certification Official (TCO) verifies all labels and markings and the SWB is loaded into a TDOP, which is then loaded into the TRUPACT-II. For TDOPs, a tamper indicator device between the lid and body flanges is applied when a tamper indicator is required [6]. This seal could potentially be used for maintaining CoK during shipment.

Once loaded, the lid is secured on each TDOP before being loaded into a TRUPACT-II and a unique identifier is attached. A vacuum is then pulled on each loaded and lidded TRUPACT-II. The vacuum for each TRUPACT-II is measured when it is placed on a transport truck for shipment to WIPP.

4.2. Shipment

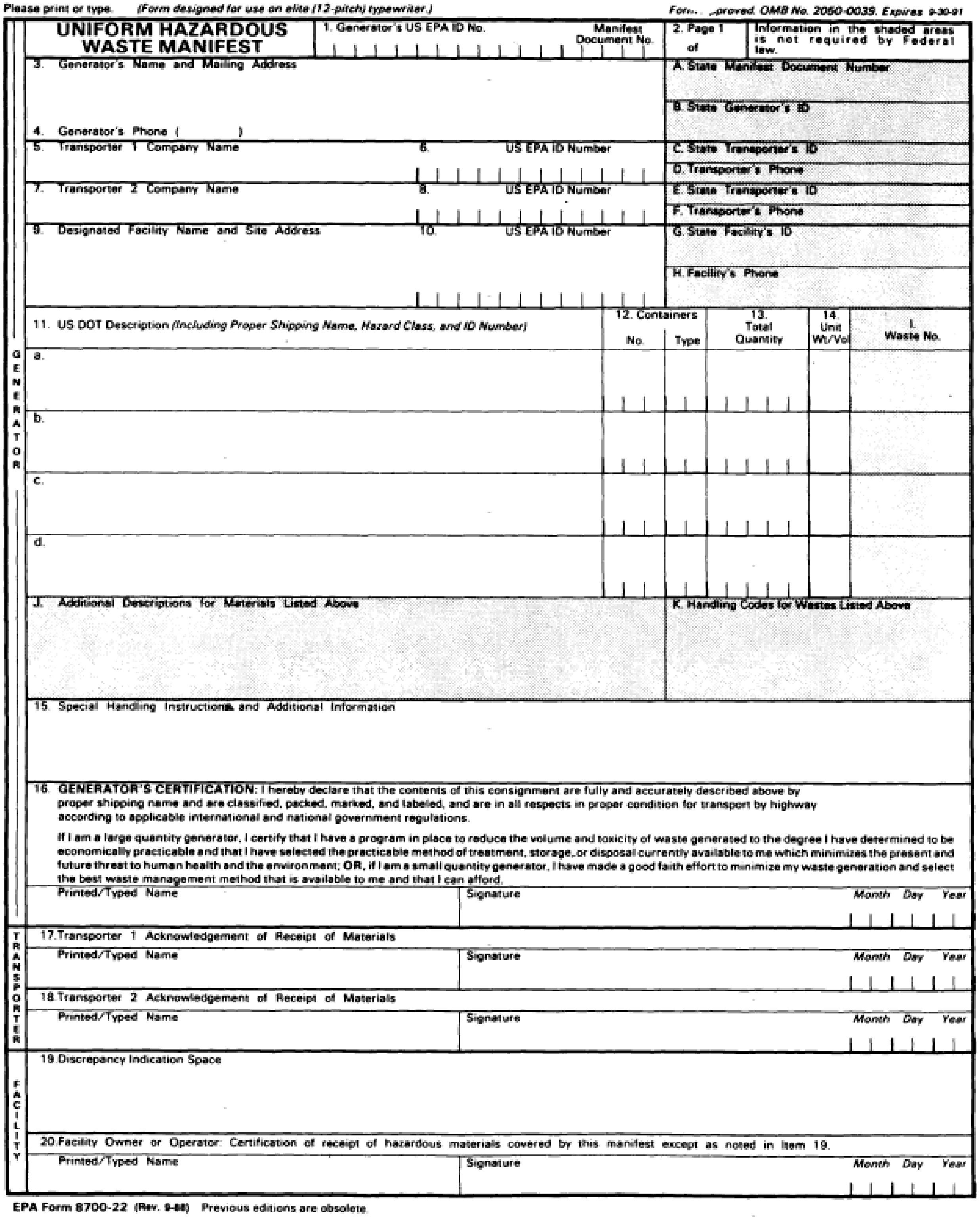
Containment and surveillance measures should provide a high level of assurance that disposal drums with plutonium wastes are received intact at the repository. During shipment, the location of each TRUPACT-II is monitored while in transit by using TRANSCOM[4] tracking (tracking is provided for security purposes). No [known] facilities *en route* (i.e., between SRS and WIPP)

[4] TRANSCOM is the Department of Energy (DOE) satellite tracking and communications system used to monitor radioactive material shipments from DOE and Nuclear Regulatory Commission (NRC) licensee facilities. https://www.energy.gov/sites/prod/files/em/transPDFs/FACTsheet-April2009rev3.pdf

have the capability to open a TRUPACT-II container or to regenerate the vacuum in the TRUPACT-II. In this way, the vacuum for each TRUPACT-II, when measured upon receipt at WIPP, can be used to help assure that the TRUPACT-II overpack has not been opened and that CoK has been maintained on the drums (and plutonium) inside each TRUPACT-II container. Nevertheless, the IAEA might require additional measures be used to assure CoK is maintained, including applying a suitable safeguards seal onto each TRUPACT-II before shipment, as well as radiation monitoring and/or video surveillance of each TRUPACT-II during shipment, to increase confidence that CoK has been maintained during shipment.

Additional procedures that support chain of custody, or possibly maintaining CoK during shipping, include close coordination between the TCO, the RCT, the Host Site Shipping Coordinator, and the WCO. For example, prior to shipment, one of the responsibilities of the RCT is to ensure that visible container identification (ID) labels, within a payload assembly, are an exact match to the ID numbers listed [8]. The Host Site Shipping Coordinator also provides data received from the TCO to the Host site transportation and material control/accountability groups (as applicable), which could be relevant for confirming shipper/receiver difference, should it be necessary. There are also specific procedures for labelling and uniquely identifying packages, SWB, 55-gallon drums, TDOPs and TRUPACT-II overpacks. Labels document information such as Manifest Number, Outer Containment Assembly (OCA) lid numbers, Closure Lid (CL) numbers, Inner Containment Vessel (ICV) closure data and time, dose rate, alpha, beta and gamma contamination survey results and Reportable Quantity (RQ) or Highway Route Control Quantity (HRCQ) flags from the Bill of Lading. All data described above is entered into the WDS for appropriate tracking and record retention [8]. Prior to shipping, all visible container ID labels are verified as an exact match to the ID numbers listed on the Payload Container Transport Documents (PCTCDs) or the Payload Assembly Transport Certification Documents (PATCDs). Once all necessary labelling and marking is verified and complete, the shipment is released.

An additional DOE procedure used to assure proper chain of custody is maintained on each TRUPACT-II during shipment includes using a manifest to document the contents of and other information about each TRUPACT-II overpack (Figure 3). The manifest lists each waste drum (or unit) in a TRUPACT-II. The CCP procedures for maintaining chain of custody are followed by the contractor responsible for shipping. The manifest is checked against the TRUPACT-II contents upon receipt at WIPP (next section).


Please print or type. *(Form designed for use on elite (12-pitch) typewriter.)* Form Approved. OMB No. 2050-0039. Expires 9-30-91

UNIFORM HAZARDOUS WASTE MANIFEST

1. Generator's US EPA ID No.
Manifest Document No.
2. Page 1 of
Information in the shaded areas is not required by Federal law.

3. Generator's Name and Mailing Address
A. State Manifest Document Number
B. State Generator's ID
4. Generator's Phone ( )
5. Transporter 1 Company Name
6. US EPA ID Number
C. State Transporter's ID
D. Transporter's Phone
7. Transporter 2 Company Name
8. US EPA ID Number
E. State Transporter's ID
F. Transporter's Phone
9. Designated Facility Name and Site Address
10. US EPA ID Number
G. State Facility's ID
H. Facility's Phone

11. US DOT Description *(Including Proper Shipping Name, Hazard Class, and ID Number)*	12. Containers		13. Total Quantity	14. Unit Wt/Vol	I. Waste No.
	No.	Type			
a.					
b.					
c.					
d.					

GENERATOR

J. Additional Descriptions for Materials Listed Above
K. Handling Codes for Wastes Listed Above

15. Special Handling Instructions and Additional Information

16. **GENERATOR'S CERTIFICATION:** I hereby declare that the contents of this consignment are fully and accurately described above by proper shipping name and are classified, packed, marked, and labeled, and are in all respects in proper condition for transport by highway according to applicable international and national government regulations.

If I am a large quantity generator, I certify that I have a program in place to reduce the volume and toxicity of waste generated to the degree I have determined to be economically practicable and that I have selected the practicable method of treatment, storage, or disposal currently available to me which minimizes the present and future threat to human health and the environment; OR, if I am a small quantity generator, I have made a good faith effort to minimize my waste generation and select the best waste management method that is available to me and that I can afford.

Printed/Typed Name | Signature | Month Day Year

TRANSPORTER

17. Transporter 1 Acknowledgement of Receipt of Materials
Printed/Typed Name | Signature | Month Day Year

18. Transporter 2 Acknowledgement of Receipt of Materials
Printed/Typed Name | Signature | Month Day Year

FACILITY

19. Discrepancy Indication Space

20. Facility Owner or Operator: Certification of receipt of hazardous materials covered by this manifest except as noted in Item 19.
Printed/Typed Name | Signature | Month Day Year

EPA Form 8700-22 (Rev. 9-88) Previous editions are obsolete.

Figure 3. Uniform hazardous waste manifest (US EPA) used for shipments of TRU waste to WIPP. Manifest is used to maintain chain of custody for each waste shipment.

4.3. Receipt

Containment and surveillance measures should provide a high level of assurance that disposal drums with plutonium wastes are received intact at the repository. Once a shipment arrives at WIPP, the receiving procedure is followed: the pressure on each TRUPACT-II is checked, the vacuum released, and the TRUPACT-II lid is opened; each waste drum is then verified to be as stated on the manifest (Figure 3). If a safeguards seal has been applied, it will be verified and removed before opening the TRUPACT-II lid. Data from IAEA video surveillance cameras and/or radiation monitors, if used during shipment, will be collected and analyzed by an IAEA inspector (data analysis might be performed off-site).

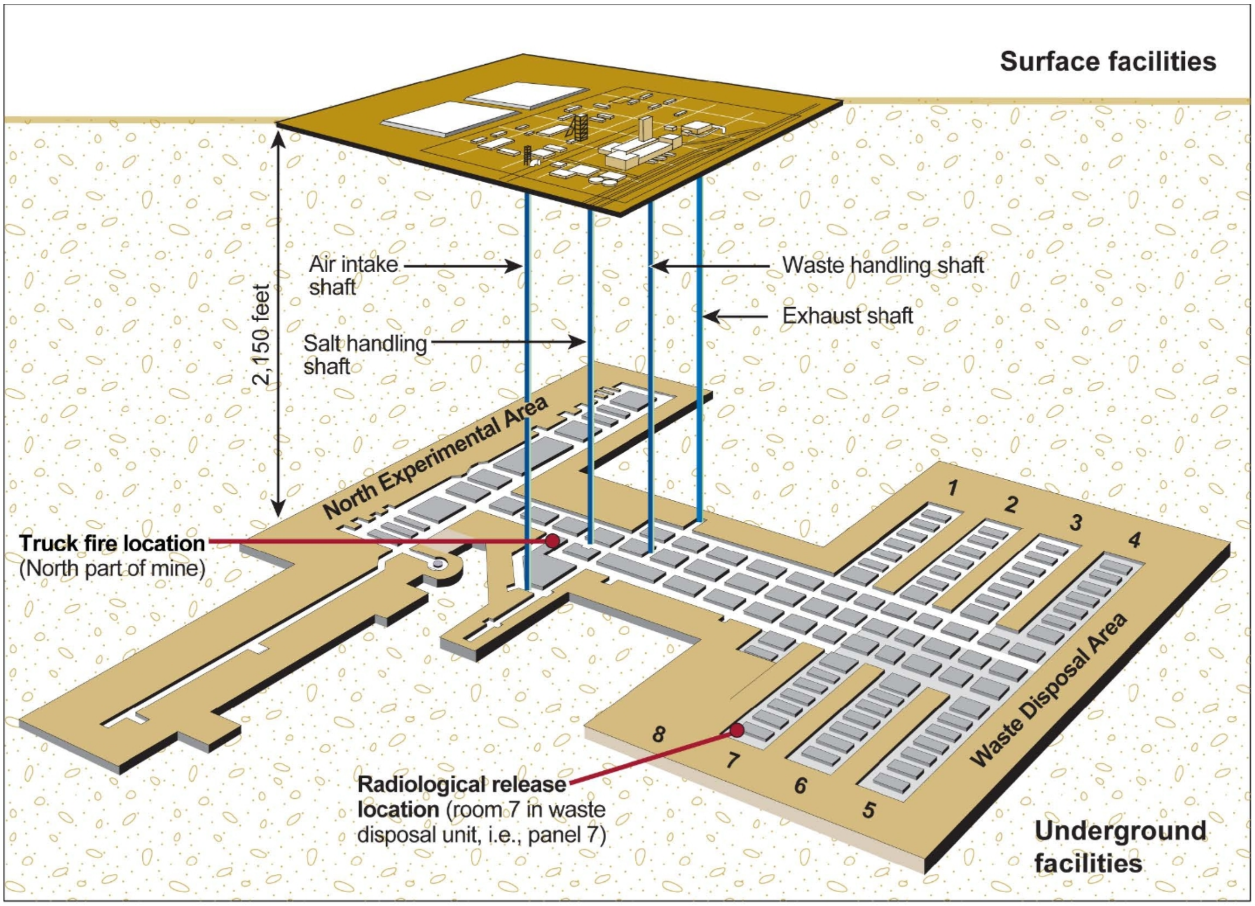
If CoK is lost on a TRUPACT-II or its contents (e.g., vacuum is compromised or a safeguards seal shows signs of tampering), the IAEA should be able to reverify waste drums after they arrive at WIPP and before they are emplaced underground. This will require a buffer storage area for such drums that is separated from unloading operations and adequately secured until the IAEA can reverify waste drums on which CoK has been lost.

4.4. Emplacement

Once received, the waste content of the TRUPACT-II containers is prepared for emplacement. A forklift transfers each TRUPACT-II from the trailer, through an air lock, into the Waste Handling Building where it will likely be stored temporarily. The TRUPACT-II is placed in a TRUDOCK, which holds the shipping container in place while workers unload the waste. An overhead crane removes lids, then removes waste containers and places them on a pallet where they will likely be stored temporarily. As noted in the previous section, C/S measures will need to be applied in the receiving hall and buffer storage area(s) to maintain CoK on waste drums until they are transferred underground.

Once the facility is prepared to take the waste drums down into the repository, a forklift moves the loaded facility pallet to a conveyance loading car inside an air lock at the waste handling shaft. A conveyance loading car is used to load the pallet onto a waste hoist (mine elevator). The waste hoist then descends 2,150 feet down to the repository. Upon arrival underground, a transporter pulls the pallet off the hoist onto a transporter bed and moves the waste to a disposal area. A forklift removes waste containers and emplaces them for permanent disposal. Ensuring that waste is emplaced as declared is covered in more detail in the next section. First, we provide a brief description of the WIPP facility's underground workings.

WIPP comprises surface facilities, underground facilities, and shafts connecting the two. Shafts include an exhaust shaft, an air intake shaft, a salt-handling shaft, and a waste-handling shaft. The underground facilities include experimental facilities as well as disposal areas (Figure 4).



Source: Department of Energy. | GAO-16-608

Figure 4. Diagram of WIPP.

The underground workings of the WIPP contain eight waste-disposal panels, with four panels on each side of the main access drifts. Each panel consists of seven rooms, each of which is 13 feet high, 33 feet wide, and 300 feet long (roughly the length of a US football field). Once a panel is filled, it is closed.[5]

The waste shaft for WIPP is the largest of the facility's shafts, at 20-foot diameter, and is used to transport employees (up to 75), equipment, and TRU waste to the underground. The salt shaft (10-foot diameter) can also be used to access the repository. The salt hoist can transport up to 15 employees, but is primarily used for removing excavated rock salt from the underground and has a load capacity of eight tons. An additional two shafts are for ventilation, comprising an air intake, which brings air to the underground, and an air exhaust, where air exits to the surface.

[5] Source: http://wipp.energy.gov/index.asp

5. ENSURING CONFIDENCE THAT WASTES ARE EMPLACED AS DECLARED

Ensuring that waste is emplaced as declared begins with verifying that a repository is constructed according to design information provided to the IAEA. Thus, before waste is emplaced in any repository, the IAEA performs one or more design information verification (DIV) inspections of the repository's surface facilities and underground workings (including shafts or other features connecting the two); these inspections assure that the repository is constructed as declared. Because an operating repository will be under continuous construction, concurrent with emplacement and backfilling operations, periodic DIV inspections will be conducted throughout the repository's operating phase to confirm that the repository continues to be constructed and operated as declared. Furthermore, periodic DIV inspections during the operational life of a repository should verify the continued integrity of the repository's geological containment, detect any unreported access points, and detect undeclared areas or activities underground that could allow waste to be removed from the repository, as well as any undeclared capabilities to reprocess the waste. With a repository's design verified, the IAEA can implement C/S measures to ensure that all access points are monitored to ensure that no waste can be removed without being detected.

Containment and surveillance measures should provide a high level of assurance that plutonium waste received at the geological repository is transferred underground for emplacement. Containment and surveillance measures should also provide a high level of assurance that plutonium waste cannot be removed undetected from the repository through declared connections [access points] between the repository underground area and the surface (ramps, material shafts, ventilation shafts, and boreholes) and that any undeclared excavation activities to connect the underground area with the surface be detected. The level of assurance should be equivalent to that provided by dual C/S if the plutonium waste is considered "difficult to access," as for plutonium waste after it has been emplaced underground. That is, each plausible diversion path must be covered by two C/S devices that are functionally independent and not subject to a common tampering or failure mode [9, p. 15].

It is currently unknown if seals will be verified and removed at surface facilities (i.e., under surveillance by the waste shaft) or underground facilities, or if seals will be verified but left on the waste drums. Seals could feasibly be left on waste drums during emplacement, but verification would be difficult if not impossible, and it is uncertain how long seals could be left on waste drums before failure or deterioration. Because of this, it is recommended that C/S measures are deployed in locations that can be maintained and accessed.

We do not recommend sealing underground rooms or panel doors because of the extra resources required to apply, verify and remove (if necessary) such seals during emplacement operations. Although seals could be attached to doors after emplacement in a room or panel is complete, C/S measures would still be required during the emplacement process. It would be more efficient to monitor the four shafts that provide access to the repository. Dual C/S measures at these locations could include optical surveillance triggered by, for example, motion detectors, laser curtains, or radiation detectors. Paired radiation detectors could be deployed at shaft entrances as to determine direction that waste drums are moved. These C/S measures should operate in unattended mode with remote transmission of data capabilities, should function for long periods of time with minimum or no service (even in rugged environments), and must meet rigorous system specifications and standards.

6. CONTAINMENT AND SURVEILLANCE: APPROACHES AND TECHNOLOGIES FOR SPENT FUEL WITH POTENTIAL APPLICATIONS TO WIPP

The IAEA is required to verify all NM under safeguards. After NM has been verified by a suitable accountancy measurement (e.g., see Appendix A.4 and [10]), C/S measures are applied to maintain CoK on the verified NM. The requirement for verification and CoK ends only if the IAEA has agreed to terminate safeguards on the waste ("measured discards") or has exempted the nuclear material from safeguards (see Section 7 and reference [11]). If safeguards cannot be terminated, CoK must be maintained on the waste "for as long as the safeguards agreement remains in force." [5]

At the highest level, the role of C/S for repositories is to maintain CoK on accountable waste material under safeguards following the last accountancy measurement until final disposal. C/S measures for transportation and packaging must be considered, as these comprise a significant part of the challenge to confidently maintaining CoK on wastes. Once waste is emplaced in a geological repository, C/S and monitoring measures will be the only safeguards tools capable of maintaining CoK on the repository contents [12]. The IAEA has considered safeguards for SNF destined for disposal in geological repositories (see Appendix A) but has not specifically addressed safeguards for other accountable nuclear materials declared as waste that will, like SNF, remain under safeguards indefinitely. For packaging, transport and receipt of these other types of NM, lessons can be drawn from existing safeguards approaches and C/S measures.

6.1. Safeguards measures potentially applicable at SRS during packaging for shipment and disposal

Plutonium wastes will be packaged for shipment at the SRS. If the IAEA performs a final safeguards accountancy measurement on the waste drums at SRS, CoK will need to be maintained by applying suitable C/S measures from the final accountancy measurement (waste verification) through placement of the verified waste drums into shipping containers (TRUPACT-II). C/S will need to be maintained until the TRUPACT-II containers that contain the verified waste drums are loaded onto transport vehicles for transport to WIPP. From a safeguards perspective, C/S measures to be applied at the SRS packaging facility might be similar to those recommended by the IAEA for a spent-fuel encapsulation plant [13]. For the most part, C/S measures to be applied to encapsulation plants will be more-or-less standard equipment, such as radiation monitors and surveillance cameras, and we envision similar C/S measures to be implemented at the SRS packaging facility to maintain CoK on verified waste drums being prepared for shipment at the SRS, with a possible exception for whether the IAEA determines that dual C/S measures will be needed to maintain CoK on verified waste drums or TRUPACT II shipping containers during shipment to WIPP.[6]

[6] In a dual containment and surveillance system, each plausible diversion path is covered by two containment or surveillance devices that are functionally independent and are not subject to a common tampering or failure mode. 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 CoK has been maintained. If either one should verify negatively, CoK has been lost [9, p. 15].

Surveillance cameras are perhaps the most likely C/S measures to be used following the final verification measurement and during packaging of verified waste drums for shipment. Cameras would need to be placed in the SRS packaging area so that they have clear views of waste drums where final accountancy measurements are made and of all packaging operations, including placement of waste drums in TRUPACT-II shipping containers, sealing of TRUPACT-II containers (if applicable), and placement of TRUPACT-II containers on transport vehicles for shipment to WIPP. Surveillance cameras would also be recommended for any buffer storage areas at SRS that might hold waste-loaded TRUPACT II containers awaiting shipment, although radiation detectors might also be used in a storage area to monitor waste drums.

6.2. Safeguards measures potentially applicable during transport

Transportation is a crucial link between the final accountancy measurement for safeguards and final disposal. Because there is potential for diversion during transportation, C/S measures need to be applied to shipping containers from the time they leave the encapsulation plant, such as SRS, until they are received at a repository such as WIPP. Because it is feasible (though not preferable) to reverify disposal drums after they have been removed from a shipping container but before they have been transported to the repository's underground, dual C/S measures(see footnote 6) may not be needed during transport. That is, the employment of at least two independent methods for assuring CoK whereby both measures must verify positively to be able to conclude that CoK has been maintained may not be necessary. Thus, the safeguards measures during transport could be minimal, including a surveillance camera, a single seal, or a mobile unit for neutron detection (MUND) .

A MUND is used to monitor neutron-emitting NM, such as spent-fuel assemblies and SNF disposal canisters, by measuring neutron count rate. The MUND is an all-in-one neutron detection system that collects and stores data and can run in stand-alone mode on battery power. Each MUND uses a ^{3}He detector mounted inside a polyethylene moderator slab and integrated with all the supporting electronics inside a single, sealable enclosure. Once installed, a MUND is usually serviced by replacing the unit with a fully recharged unit. A MUND can collect data for more than eight weeks without service [12, p. 63].

MUND detector systems are most commonly used to maintain CoK during transfers of spent fuel from a reactor building's storage pond to a dry-storage facility, but has also been used to monitor transfers of spent fuel between storage ponds. Both applications are currently used as part of a dual C/S system at two nuclear power reactors in Argentina [14]. In the case of plutonium waste shipments from SRS to WIPP, a MUND could be applied to each TRUPACT II shipping container as it is loaded at SRS with waste drums and kept on each TRUPACT II until it has been unloaded at WIPP. If the IAEA determines that dual C/S is necessary during shipment, a MUND could be one of two independent C/S systems.

Although beyond the scope of this study, the need for seals on transport casks that could be both applied and removed by an operator has been addressed elsewhere. [15]

6.3. Safeguards measures potentially applicable during receipt of nuclear material at a repository

The receiving and storage area of a repository is where waste is delivered and disposal canisters (if SNF) or waste drums (in the case of WIPP) are removed from shipping containers. The receiving area at WIPP is the Waste Handling Building (Section 4.4). SNF canisters or waste drums may be put into a buffer storage area before being emplaced in the repository. While waste containers are being stored for emplacement, C/S measures will be needed at the buffer-storage area to maintain CoK on the waste to be emplaced. Surveillance of the storage area by using cameras and radiation monitors would detect movements of transport casks or waste containers.

Access points to a repository during the operational phase will need monitoring for potential diversion. Applicable C/S measures at access points include radiation detectors (possibly paired directional detectors) to ensure no waste can be returned to the surface via such points undetected. Some of the recognized challenges for radiation monitors include detecting waste-generated radiation through mined rock debris that might be used to hide waste containers. Using laser scanning to monitor movements (and shapes) is another possible C/S measure. No single monitoring method or measurement would suffice to provide unambiguous confirmation about possible diversion attempts (or the lack thereof). For this reason, 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.

The IAEA has allowed C/S equipment (primarily seals) to be applied by a State/operator under special conditions at either the shipping or receiving end of a shipment. The IAEA must validate that the C/S was effectively applied to a shipping container. If the IAEA does not verify C/S at either end, it has no assurance that the container was not opened undetected because of ineffective or fraudulent use of the C/S system. The IAEA has proposed an alternative approach whereby the State/operator applies C/S equipment, the inspector inspects the C/S in an interim storage location where multiple items are accumulated to await shipment or disposal, after which the State/operator can remove the C/S equipment. This has been addressed in more detail elsewhere [15, 16].

Emplacement at WIPP will have similar CoK requirements, approaches, and technologies. Section 5 gives more details on this.

7. OPTIONS FOR TERMINATING INTERNATIONAL SAFEGUARDS

Whereas safeguards cannot be terminated based on the type of facility in which nuclear materials reside (e.g., a repository), the IAEA does allow safeguards to be terminated on nuclear material according to the safeguards agreement between the IAEA and the State.

Two primary conditions for terminating safeguards on nuclear materials are described in paragraphs 11 and 35 of INFCIRC/153. The first of these concerns the consumption or dilution of nuclear material. Safeguards may be terminated on nuclear material that has been subject to safeguards under a safeguards agreement when the IAEA determines that the nuclear material "has been diluted in such a way that it is no longer usable for any nuclear activity relevant from the point of view of safeguards, or has become practicably irrecoverable" (INFCIRC/153, paragraph 11). Nevertheless, the State is required to provide the IAEA with information regarding the location or further processing of intermediate or high-level wastes that contain Pu, high-enriched uranium (HEU) or uranium-233 (233U), on which safeguards have been terminated (Article 2.a.(viii) of INFCIRC/540).

Paragraphs 13 and 35 of INFCIRC/153 and paragraph 27 of INFCIRC/66/Rev2 state that, "safeguards may be terminated for material transferred to non-nuclear use, such as the production of alloys or ceramics." It might be argued that the production of waste forms for permanent disposal underground is a non-nuclear use, and that such waste forms are most likely to be crystalline ceramics, glasses and alloys.

Where the above conditions are not met, but the State considers that the recovery of safeguarded nuclear material from residues is not, for the time being, practicable or desirable, the IAEA and the State should consult on the appropriate safeguards measures to be applied. By agreement between the IAEA and the State, safeguards can be terminated on nuclear material subject to safeguards under the conditions set forth in the previous paragraphs, provided that the State and the Agency agree that such nuclear material is "practicably irrecoverable."

Determining what is "practicably irrecoverable" will depend upon the waste material type, its nuclear material composition, chemical and physical form, and waste quality (e.g., the presence or absence of fission products). The total quantity, facility-specific technical parameters, and the intended method of eventual disposal might also be considered [17]. Conditioned wastes emplaced and sealed in a deep geological repository are *prima facie* unattractive sources of nuclear material, and it has been suggested that safeguards be terminated "at this point or before" [17, p. 24]. However, there is no waste form from which nuclear material cannot be recovered if cost is not an issue [17, p. 24], and future technological innovations may well provide ready means to recover nuclear material on which safeguards had been terminated.

The IAEA has identified three fundamental safeguards concerns related to nuclear waste materials [18, 19]. One is that the waste itself might be diverted and processed to recover the nuclear material for subsequent use. The other is that a State may deliberately overstate the nuclear material content in waste that is subject to termination of safeguards. If the content of NM in the waste is overstated, it could enable actual removal (i.e., diversion) of that excess U or Pu from elsewhere in the facility. Both concerns demonstrate the need for accurate safeguards-verification measurements. The IAEA has not indicated what practical methods or level of effort correspond to making nuclear materials "practically irrecoverable"; however, the IAEA has determined a set of provisional criteria for terminating safeguards for nuclear material in certain types of conditioned waste [11]. For Pu in a waste glass, the IAEA recommends that 2.5 kg-Pu per cubic meter (kg-Pu·m^{-3}) of vitrified waste is the concentration at or below which Pu in the vitrified waste can be considered practically unrecoverable and safeguards terminated. For waste conditioned by encapsulation in cement, such as hulls, proposed concentration limits are lower. See Table 1.

Table 1. Provisional IAEA Criteria for Terminating Safeguards on Selected Conditioned Wastes Containing Plutonium *

	Waste Form or encapsulation method	
Waste Stream	**Glass (VWF)**	**Cement**
High-activity liquid	2.5 kg-Pu·m^{-3}	---
Feed-clarification sludge	2.5 kg-Pu·m^{-3}	2.0 kg-Pu·m^{-3}
Hulls	---	1.2 kg-Pu·m^{-3}

**Source: Table 1 of Reference [11, p. 206].*

The focus here is on IAEA's provisional criteria for terminating safeguards on vitrified waste [11] as an appropriate approximation for Pu-bearing wastes destined for WIPP. We can also note that some waste forms may not always contain the elements of interest, including Pu, in solid solution (*i.e.,* uniformly distributed) within their matrices; this might be true of Pu-bearing wastes for WIPP as well. Such elements may occur as inclusions of separate phases [20, 21], a phenomenon that can become increasingly common at high waste loadings. In a situation where a waste form contains physically separate inclusions of, for example, PuO_2 [20], physical grinding and concentration by gravity or similar means might be used to help separate such inclusions from the bulk waste form, potentially reducing effort required to recover nuclear material contained in the inclusions.

There is a second concern identified by the IAEA: overstating the NM in a waste stream [19]. Whereas recovering nuclear material through processing of waste material is the more commonly recognized concern, from the standpoint of terminating safeguards, deliberately overstating the content of nuclear material in the waste is probably the more important concern. Detection of diverted material provides the primary deterrent against diversion. Diversion of nuclear material under safeguards is detected by evaluating material unaccounted for (MUF) during material-balance periods. If a State falsifies the amount of nuclear material in the waste by overstating the amount, and the falsification is not detected through verification, then the falsification will never be detected, because the quantity represented by the falsification no longer exists in the safeguarded material balance (and is therefore not included in MUF).

Considering the two concerns addressed above (dilution and falsification), the actual nuclear-material content of waste discards may not be as important as assuring that the stated nuclear material content in the waste is measured correctly and verified [18].

The third major concern is the potential for the reintroduction of wastes for which safeguards have been terminated [22]. Reintroducing waste on which safeguards have been terminated would enable a State to divert NM from elsewhere. This requires some assurance that wastes with NM on which safeguards have been terminated exit the process for eventual disposal. Once measurements have verified waste Pu inventory for safeguards purposes, some means of maintaining CoK though C/S measures will be needed.

Plutonium wastes packaged for disposal at WIPP will be conditioned before being placed into waste drums by “downblending” the plutonium in a waste matrix [8], the composition of which is not available. Whether IAEA safeguards could be terminated on the downblended plutonium waste is unknown and would be based on agreement between the IAEA and the US. Nevertheless, even following termination of safeguards, there still need to be assurance that the waste is disposed as declared, so maintaining CoK on the waste until emplacement in the WIPP repository would still apply.

8. CONCLUSIONS AND RECOMMENDATIONS

Maximizing confidence in maintaining CoK on plutonium-bearing wastes, such as that shipped from SRS to WIPP, from a final safeguards-verification measurement through emplacement underground, will require C/S measures that can be applied during packaging, shipment, receipt and emplacement. This study explored both IAEA and WIPP procedures for maintaining CoK on waste NM to glean potential safeguards applications for countries with a CSA that plan to dispose in a geological repository plutonium or other non-fuel nuclear materials that are under international safeguards. While most IAEA safeguards procedures and C/S applications typically applied to SNF could also be applied to other waste NM, the study found that some procedures used for WIPP shipments may not be sufficient for international safeguards. For example, the fact that material content of Pu-bearing waste at SRS is not verified prior to shipment to WIPP is a gap, one that would have to be filled in order to satisfy international safeguards requirements [see section 4.1, p. 14]. Nonetheless, the study concludes that maintaining CoK on the non-fuel waste NM via C/S should be relatively straightforward at each step of the disposal process. These procedures might include the following summarized methods for a geological repository as they might apply to separated plutonium-bearing waste to be emplaced for disposal at WIPP (adapted from [12].

Waste to be packaged for shipment will be verified by the IAEA before it is placed into a shipping container, probably by non-destructive assay (NDA). Verification and packaging for shipment will be performed at the SRS, which is the originating point for the plutonium wastes. After this verification measurement, the waste must be maintained under C/S until it is packaged for shipment and disposal.

We assume for the purposes of this report that Pu-wastes will be packaged in a standard 55-gallon drum for disposal, and that the IAEA's verification measurement is performed on each waste-containing drum before each drum is placed into a TRUPACT-II shipping container; each TRUPACT-II is designed to contain 14 55-gallon disposal drums or one TDOP.[7]

Recommended C/S measures to be applied during packaging include surveillance cameras in the packaging area with clear views of waste drums where final accountancy measurements are made as well as views of all packaging operations, including placement of waste drums in TRUPACT-II shipping containers, sealing of TRUPACT-II containers (if applicable), and placement of TRUPACT-II containers on transport vehicles for shipment to WIPP.

Once filled and closed, TRUPACT-II shipping containers might be kept under C/S during storage and transport; this could be achieved by applying one or more safeguards seals to each TRUPACT-II shipping container, although alternative (or additional) C/S measures might be used during transport (e.g., video camera(s) for surveillance, location tracking, radiation monitors and neutron detectors). Disposal drums in a shipping container that have been kept under successful C/S are not required to be re-verified before they are emplaced underground, as CoK will have been maintained from the last safeguards verification measurement at SRS until the drums have been received at WIPP for disposal.

After wastes have been received at WIPP and their receipt documented, each TRUPACT-II shipping container is opened and the waste-containing disposal drums removed. This operation

[7] There is also a possibility that a HalfPACT shipping container might be used. Each HalfPACT is designed to contain *seven* 55-gallon disposal drums.

occurs in the receiving hall at WIPP. The receiving hall has a buffer-storage area for waste drums to be emplaced underground. A vertical elevator, located at one end of the receiving hall, transports waste drums from the receiving hall to the underground repository. C/S measures must be employed in the receiving hall to maintain CoK on waste drums from the time that a TRUPACT-II shipping container is opened (safeguards seal removed) and the drums removed, while the drums are in the receiving hall (e.g., while in buffer storage) until they are loaded onto the elevator for transport underground.

In order to maintain CoK on Pu wastes after they have been emplaced underground for disposal, IAEA policy stipulates that dual C/S measures[8] be applied to a repository, which reflects the fact that emplaced wastes are inaccessible, that is “difficult to access” according to the IAEA. [5, 9] Waste drums cannot be re-verified after they have been emplaced underground, and the repository becomes the containment for all waste underground. CoK must be maintained on the repository’s contents by applying dual C/S measures to the repository.[8] Should the non-fuel waste NM meet the criteria outlined in section 7, safeguards could be terminated, though the determination will depend heavily on the terms of the safeguards agreement between the State and the IAEA.

[8] In a dual containment and surveillance system, each plausible diversion path is covered by two containment or surveillance devices that are functionally independent and are not subject to a common tampering or failure mode. [9, p. 15]

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APPENDIX A.

A.1. History and Background of ASTOR

The IAEA began to consider appropriate safeguards for wastes proposed for disposal as measured discards and SNF to be emplaced in geological repositories in the mid-1980s. In 1988, the IAEA hosted an Advisory Group Meeting (AGM-660) to develop policy recommendations on terminating IAEA safeguards on SNF and waste. The participants, representing 16 States, recommended that the IAEA should not terminate safeguards on SNF before or after emplacement in a geological repository [23]. Consultants meetings were held in 1991 [24] and 1995 [25] to develop recommendations to the IAEA on requirements, methodology, and policy for implementing safeguards on the final disposal of SNF. In 1997, the IAEA held a second Advisory Group Meeting (AGM-995) [26] to review and make recommendations on conceptual safeguards approaches and IAEA's draft internal policy paper on the topic, which was issued later in 1997 (as Safeguards Policy Paper 15 [5]). An underlying concern of all three meetings was that safeguards must be compatible with the safety requirements developed for these facilities.

In 1994, the IAEA organized the Member State Support Program task "Programme for the Development of Safeguards for the Final Disposal of Spent Fuel in Geological Repositories (SAGOR)". Eight Member States participated in this program. The recommendations of this structured study were documented in STR-312 [27], which comprised five volumes—summary, encapsulation plants, operating repositories, closed repositories, and supporting technical reports. Each of the facility-specific volumes included a generic facility design; an assessment of diversion paths and potential detection points for each path; safeguards objectives; potential safeguards measures; candidate safeguards approaches; a recommended safeguards approach; and research and development needs.

SAGOR was followed by the SAGOR-II program which (a) assessed the safeguards measures proposed by SAGOR [27] as needed to implement the safeguards concepts; (b) addressed facility-specific considerations with respect to the SAGOR recommendations; and (c) assessed how the safeguards approaches should change under Integrated Safeguards of the State-level concept. The SAGOR-II meetings were jointly supported by IAEA's Departments of Safeguards, Nuclear Safety and Security, and Nuclear Energy. Safeguards technical reports were issued on *Geophysical Techniques* [28] and the *Interface of IAEA Safeguards with Geological Repository Operations, Safety, and Security* [29]. The latter report sought to identify operational safety and security information generated for a repository that might also be relevant to international safeguards. In addition to the Department of Safeguards technical reports, the Department of Nuclear Energy issued a report titled *Technological Implications of International Safeguards for Geological Disposal of Spent Fuel and Radioactive Waste* [30].

In 2005, the focus of the geological repository safeguards development activities was changed to perform assessments and make recommendations to support the IAEA's preparations for implementing safeguards for specific repository programs, with the first being in Finland and Sweden. The program was renamed Programme for the Application of Safeguards to Geological Repositories (ASTOR). ASTOR focused on practical aspects for implementing an integrated safeguards approach for a generic SNF encapsulation plant and geological repository site and on safeguards techniques applicable to specific geological repository designs. During the ASTOR project, other Member State Support Programme tasks were ongoing related to specific technologies being developed for geological repository safeguards (e.g., satellite imagery and SNF measurement), and meetings were being held by IAEA with Finland, Sweden, and the European Commission to develop facility-specific safeguards approaches. ASTOR was briefed on the status and findings of these tasks and meetings. ASTOR reviewed and provided advice on model integrated safeguards approaches and design information questionnaires developed by the IAEA for encapsulation plants and operating geological repositories.[9] ASTOR also reviewed information input to the draft design information questionnaires prepared by Finland and Sweden on their encapsulation plants and geological repositories and provided recommendations for improving the questionnaires. ASTOR also reviewed the 'road map' for safeguards implementation prepared by the IAEA Safeguards Operations Division C. After its second five-year period, ASTOR issued the report titled *Technologies Potentially Useful for Safeguarding Geological Repositories* [12].

A.2. IAEA Recommended Approaches for Geological Repository Safeguards

Under a CSA, the objective of IAEA safeguards is the "timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection" (INFCIRC/153) [31]. For States that have adopted the Additional Protocol (AP), safeguards are also meant "to provide credible assurance of the absence of undeclared nuclear materials and activities in a State" (INFCIRC/540) [32].

With respect to safeguards for geological repositories, IAEA policy states that, "Spent fuel disposed in geological repositories is subject to safeguards … for as long as the safeguards agreement remains in force." [5] Because the IAEA considers all known design concepts for mined geological repositories to be inherently retrievable, regardless of whether retrievability is intentionally integrated into the repository design and management, permanent disposal does not terminate IAEA safeguards on SNF. Safeguards measures that can achieve the IAEA's safeguards objectives will therefore apply indefinitely to geological repositories [33].

IAEA policy states that the safeguards approach for a geological repository should be based on the following criteria. [5]

1. verifying design information during design, construction, and operation;
2. verifying receipts and flows of nuclear materials;
3. maintaining CoK on nuclear material content;
4. verifying nuclear material contents of incoming disposal containers; and
5. maintaining CoK of the nuclear-material inventory.

Although current IAEA policy refers explicitly to SNF, the same criteria can be applied to all accountable nuclear materials declared as waste; *i.e.*, waste nuclear materials subject to IAEA safeguards (referred to as "measured discards"). Once safeguarded waste has been emplaced underground in a repository, it cannot be re-verified (i.e., no NDA measurements can be

[9] Advice was also provided by the IAEA Director General's Standing Advisory Group on Safeguards Implementation

performed on waste underground), placing unprecedented reliance on C/S measures to maintain CoK on waste. As noted in Section 3, the focus of this report is on bullets 3 and 5.

A.3. Integrated Safeguards

Integrated safeguards refer to the optimum combination of all safeguards measures available to the IAEA under comprehensive agreements and additional protocols to achieve maximum effectiveness and efficiency in meeting the IAEA's safeguards obligations within available resources [34]. Integrated safeguards are implemented in a State only when the IAEA has drawn a conclusion of the absence of undeclared nuclear material and activities in that State. Under integrated safeguards, measures may be applied at reduced levels at certain facilities, compared with the measures that would have been applied without this conclusion.

Both SAGOR and ASTOR have made recommendations on integrated safeguards approaches for geological repository facilities. Initial work of ASTOR supported preparation of model integrated safeguards approaches and design information questionnaires for encapsulation plants and operating geological repositories. In addition, the IAEA has established a *Model Integrated Safeguards Approach for a Geological Repository* [9] that provides guidance for preparing a safeguards approach for a geological repository in a State under integrated safeguards. Measures include: design information verification (DIV), physical inventory verification (PIV), verification of receipts and shipments, verification of transfers between above-ground and geological repository areas, and interim inspections.

To provide assurance that undeclared removal of material from the geological repository does not occur through a declared access route or through an undeclared route, the safeguards measures should monitor all transport vehicles leaving the geological repository, monitor other safeguards relevant access routes into the geological repository, and confirm the continued integrity of containment provided by the geological formation, within which is defined a "restricted zone" where no mining operations are permitted [9]. C/S measures will provide much of this assurance.

A.4. Methods used by IAEA for measuring plutonium

The IAEA has focused much of its effort on safeguards for geological repositories on maintaining CoK on SNF, including the ability to detect SNF by monitoring for the characteristic radiation it emits. The most penetrating gamma radiation emitted by SNF is from fission products such as cesium-137 and strontium-90; however, nuclear material (uranium and plutonium) in SNF also emit neutrons, which can help distinguish SNF from potential "dummy" substitutes that might mimic gamma emissions from SNF but which contain no uranium and plutonium and therefore does not emit neutron radiation.

The plutonium waste to be shipped to WIPP is incorporated into a waste form that will be packaged in 55-gallon waste drums. The IAEA will verify the plutonium content of each drum, most probably by combining gamma and neutron measurements as described below. Following this verification measurement, which will be the final safeguards measurement on the plutonium waste before it is shipped to and disposed at WIPP, CoK will need to be maintained on the waste until it is emplaced underground.

Maintaining CoK on the plutonium inside the waste drums might include, in addition to sealing each TRUPACT-II shipping container, monitoring the waste drums and TRUPACT-II shipping casks that contain the plutonium waste for neutron and/or gamma radiations that the plutonium emits. Measuring neutron and gamma spectra for each drum when it is received at WIPP might be sufficient to determine if each spectrum matches that collected during the final accountancy measurement performed at the shipping point (i.e., the SRS). However, this would require a unique identifier for each waste drum.

Plutonium-239 and its progeny emit a low-energy gamma ray that can be absorbed by the waste-matrix or other materials (e.g., cask or canister materials) and can also be difficult to detect due to interference by natural background signals in the same energy range. However, plutonium can also be measured indirectly by measuring the 60-keV gamma ray emitted by Am-241, a daughter of Pu-241. By combining the measured gamma spectrum with knowledge about the original assay and age of a plutonium sample, the plutonium-americium ratio can be computed and total plutonium determined.

A plutonium sample assay can be verified by measuring neutron emissions. Neutrons are emitted from plutonium primarily in three ways:

(1) *Spontaneous fission*, mainly by even isotopes of plutonium;

(2) *Induced fission* from fissile isotopes of plutonium by neutrons from other sources (including external sources if present);

(3) *Alpha-particle-induced reactions* (α,n) involving light elements such as oxygen and fluorine.

Fission neutrons in the first two categories are emitted at rates of 1 to 10 neutrons per fission event. Alpha (α) particles emitted by plutonium can interact (via [α,n] reactions) with light elements that might be present in, for example, the waste matrix (e.g., oxygen, fluorine, boron, beryllium, lithium) to produce a time-constant neutron background. *Neutron coincidence counting* can be used to distinguish neutrons emitted from a single fission event from those created by other processes, including secondary fission events and [α,n] reactions with a uniform time distribution. Neutron coincidence counting discriminates against this [α,n] background by tracking the time between neutron detections. Neutrons from a single fission event are detected relatively close to each other in time, whereas neutrons from non-fission processes such as [α,n] reactions are randomly distributed over time.

Passive coincidence detector systems are used to determine the mass of plutonium based on spontaneous fission, primarily in the even numbered isotopes (Pu-240 is the dominant contributor). The major fissile isotope, Pu-239, has a typical abundance of 60% or more but contributes little to a spontaneous-fission neutron signal. A sample's isotopic abundance must be known or verified, typically by means of a high-resolution gamma- measurement (see above). By determining isotopic abundance, the mass of Pu-240(effective) determined from coincident neutron count rates can be converted to total plutonium. Therefore, both gamma and neutron measurements are generally needed to quantify the mass of plutonium in a sample.

Multiplicity coincidence counting uses additional information from fission events for which at least three coincident neutrons are detected per event (triples). The measurable multiplicity distribution can be used to solve for three unknowns, the mass of Pu-240(effective), multiplication, and the (α,n) neutron rate, with which the mass of plutonium in a sample can be calculated directly. Multiplicity coincidence counting requires high-efficiency detectors, as the detected triples rate is proportional to efficiency cubed, and multiplicity counters are designed to minimize die-away time and dead time. Although conventional neutron coincidence counters can be used for multiplicity analysis, their lower efficiencies and longer die-away times require longer counting times and result in lower precision in the triples rate.

Low- and medium-resolution gamma spectrometry measurements range from quantitative verification of enrichment levels to the purely qualitative detection of plutonium and uranium, and of the presence of nuclear material in general.

ECGS Electrically cooled germanium system Verification of U enrichment and Pu isotopic composition in non-laboratory environments.

IMCN, IMCC, and IMCG: *InSpector 2000*® multichannel analyzer (IMCA) paired with either a NaI (IMCN), CdZnTe (IMCC) or HPGe (IMCG) detector, used for verifying U enrichment, SNF, and Pu isotopic composition.

HM-5. The HM-5 field spectrometer (HM-5) (Fig. 5) is a battery powered, hand-held, digital, low resolution γ spectrometer. This lightweight, easy to operate device is regularly used by safeguards inspectors. It combines various functions such as dose rate measurement, source search, isotope identification, active length determination for fuel rods and assemblies, determination of the enrichment of non-irradiated uranium materials, and plutonium/uranium attribute verification.

The basic HM-5 modular design includes a NaI detector. For special applications the NaI detector can be replaced with a more stable, higher resolution CdZnTe detector. Up to 50 γ spectra, each with 1024 channels, can be stored in the non-volatile memory of the HM-5 and later transferred to a computer for further processing or plotting. With such versatility, the HM-5 is used for traditional safeguards inspections and for investigations during complementary access performed under additional protocol provisions.

FMAT. The fresh MOX attribute tester (FMAT) consists of a stainless-steel cylinder housing, a lead or tungsten shield for collimation, a CdZnTe detector and a preamplifier. A multi-wire cable connects the submersible (waterproof) measurement cylinder and associated electronics (operated above water). The FMAT can clearly distinguish between the γ rays of 235U (186 keV) and 241Pu (208 keV), and uses the measurement of key plutonium γ rays as evidence that an item being measured has the characteristics of fresh mixed U–Pu oxides (MOX).

A.4.1. Neutron coincidence counting

Neutron coincidence counting has evolved into a very stable, reliable and accurate technique for determining plutonium content. Modern, well designed neutron coincidence systems are capable of reliably processing pulses over a very large range of input count rates (i.e. over more than six orders of magnitude). Stability is achieved by judicious selection and placement of amplifier electronics to minimize noise interference. The electronics boards, when located at the detector head, amplify and shape the pulses, apply lower level discrimination to remove γ pulses or noise, and feed out very narrow (50 ns wide) logic pulses to an external pulse processor (the electronics controller).

Distinguishing between time-correlated fission neutrons and random neutron events is possible because of a sophisticated pulse-processing circuit (shift-register electronics) in the external electronics controller. Neutron pulses occurring within a specified time can be termed correlated (‘coincident’). The correlation time is associated with the slowing down of neutrons in the moderator of the detector head (typically about 60 microseconds). The shift register electronics circuitry keeps track of coincidences between pulses separated by about 1000 microseconds (called ‘accidentals’) and coincidences in the first 64 microseconds (called ‘real coincidences plus accidentals'). Analysis software subtracts accidentals data from 'real coincidences plus accidentals' data to determine real coincidences.

A.4.2. Passive detector systems

Passive detector systems have two basic geometrical configurations: well detectors, which completely enclose the sample, and collar detectors, which encircle the sample (e.g. a fuel assembly). Well detectors have the preferred geometry since all the neutrons emanating from the sample enter the detector's sensitive volume. Collar detectors are an alternative design that is appropriate when the sample is too large for placement inside a well detector. Whereas calibrated passive well detectors measure the total mass of plutonium in a sample, collar detectors measure plutonium mass per unit length of a fuel assembly. The linear density must be multiplied by an active length to determine the total plutonium mass in the assembly.

About twenty kinds of passive detector systems are currently in use for nuclear safeguards, with design features optimized for specific sample sizes, shapes or plutonium mass ranges (see [10]). Four systems are described below.

HLNC. The high-level neutron coincidence counter (HLNC) is typical of IAEA well detector coincidence counting systems used for measuring non-irradiated plutonium materials. The words 'high level' are included in the name because the counting and sorting electronics can perform at a high rate, such as 100 000 counts per second. The HLNC includes a head which houses the neutron detectors (^{3}He gas proportional counters) connected to special amplifiers. The electronics controller, JSR-12, provides power to the amplifiers and ^{3}He tubes, and processes the train of pulses to determine coincidence events. A portable computer connected to the JSR-12 automates data acquisition, analyses and archiving. A printer, which presents the results in a concise report format, completes the detector package. This 60-kg detector features a large sample cavity and 18% neutron detection efficiency. By removing the top end cap, a container with plutonium (in pellet, powder or scrap form) can be centered in the large cavity. The sample is given an identification number in the computer, an appropriate calibration curve is selected and a count time is designated. Upon initiation of the measurement, the IAEA neutron coincidence counting (INCC) computer program automatically runs through a sequence of measurements, each of which must pass all built-in quality control criteria. When the measurements are completed, the plutonium mass is calculated and compared with the declared value to provide a quantitative verification that for typical high purity plutonium inventories is accurate to 1%.

INVS. The inventory sample (INVS) counter is used for small plutonium samples (bagged plutonium pellets, powders and solutions in vials) with much lower total plutonium content than those typically measured with an HLNC. The INVS has nearly double the neutron detection efficiency of the HLNC and is used to perform high precision measurements of small plutonium. In another version, the INVS has an inverted geometry and is permanently attached to the floor of a glovebox so that samples can be assayed for plutonium content without removing them from the glovebox. Although the cavity of an INVS is typically only about 6 cm in diameter and 16 cm high, it is well suited for samples available at facilities such as fuel-fabrication plants or on-site laboratories. The INVS provides highly reliable plutonium content verification with an accuracy of up to 1% in individual measurements. Measurement procedures are automated with the INCC program and are essentially the same as for the HLNC.

WCAS. The waste crate assay system (WCAS) measures the plutonium content of large waste containers for high and low activity waste (from a few milligrams to tens of kilograms). WCAS is a passive neutron coincidence counter operating in 4π geometry and can work in high radiation fields (up to ~1 Gy/h).

The amount of plutonium and 235U in the waste is calculated from the Cm:Pu and Cm:235U ratios, known from the stream average ratios at waste-generating sites. WCAS has a small 252Cf source of known source strength that can be positioned in an automated sequence at a fixed number of locations adjacent to the waste container wall. A measurement is taken with and without the interrogation source to determine a matrix correction factor for a given configuration.

A.4.3. Multiplicity coincidence counting equipment

PSMC. The plutonium scrap multiplicity counter (PSMC) system uses approximately 80 high pressure He-3 tubes in closely packed rings to achieve an efficiency of about 55%. The statistical precision of the triples rate for a typical high burnup MOX sample with a few hundred grams of plutonium is 1–2% for a 1000-second measurement. For impure items, assay accuracy improves by a factor of 2 to 50 compared with conventional coincidence counting analyses.

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