SANDIA REPORT

SAND2019-5194

Printed Click to enter a date

Sandia National Laboratories

Effective Access Monitoring at Geological Repositories

Robert J. Finch, Steven Horowitz, Heidi A. Smartt, Nathan Shoman, Risa Haddal, Robert P. Rechard

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

Issued by Sandia National Laboratories, operated for the United States Department of Energy by National Technology & Engineering Solutions of Sandia, LLC.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

ABSTRACT

Access points at a deep, mined geological repository (GR) for the disposal of spent nuclear fuel (SNF) and other nuclear wastes present potential diversion paths for nuclear material. Because C/S measures are not likely to be used underground, access to a GR will require unprecedented reliance on C/S measures to maintain continuity of knowledge (CoK) on SNF buried underground. We develop a model GR based on common features of GR designs from national programs in order to develop and optimize C/S measures for GR access points that maximize confidence that CoK is maintained on SNF underground. Critical acces points identified in this study are surface entrances to (1) the GR ramp (2) the excavation shaft, (3) the main elevator shaft, and (4) the ventilation shaft. The first three are considered critical detection points (DPs), whereas the fourth is considered a non-critical DP. The reason for the distinction is due to the different design capabilities of shaft components: the first three (ramp, excavation shaft, main elevator) are all capable of being used to move material from the underground to the surface, whereas the ventilation shaft is not. Such capabilities are verified during periodic design information verification (DIV) inspections.

We identified four detection points (DPs) with recommended C/S measures for each:

DP-1. Ramp entrance

Video-surveillance camera(s)

Portal-monitoring system:

- Radiation monitors (gamma & neutron), paired
- Infrared camera(s)
- Weighing scale

(option) Transport vehicle-mounted MUND (mobile unattended neutron detector)

DP-2. Excavation shaft entrance

Video-surveillance camera (triggered)

Radiation monitors (gamma & neutron)

Infrared camera

(option) Lift-mounted MUND

DP-3. Main elevator entrance

Video-surveillance camera (triggered)

Radiation monitor (gamma and/or neutron)

DP-4 (non-critical). Ventilation Shaft

Video-surveillance camera (triggered)

Radiation monitor (gamma and/or neutron).

ACKNOWLEDGEMENTS

This work was supported by the Office of International Nuclear Safeguards Concepts and Approaches Subprogram under NNSA's Defense Nuclear Nonproliferation Office of Nuclear Nonproliferation and Control.

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The disposal of spent nuclear fuel (SNF) in geological repositories (GRs) is a new challenge for international nuclear safeguards, where containment and surveillance (C/S) measures, combined with design information verification (DIV), will be the primary safeguards approach for maintaining continuity of knowledge (CoK) on SNF emplaced underground. Access points at a GR can include one or more ramp entrances for fuel-emplacement and construction operations (such as waste-rock removal and backfill), personnel and equipment access and egress, elevator and ventilation shafts, and other access points, depending on GR design. Such access points present potential diversion paths for diverting SNF from a GR. Given the likelihood that C/S measures will not be implemented underground, a GR and its access points at the surface will require C/S measures that can reliably maintain CoK on SNF buried underground, especially during operations when people, equipment, and materials (both nuclear and non-nuclear) will be regularly entering and leaving a GR.

A geological disposal facility has an above-ground area where operational support facilities will be located and an underground area (the GR) where waste will be emplaced for permanent disposal. The underground area is typically planned to be several hundred meters below ground level in a stable geological formation. This is to ensure that waste radionuclides are isolated from the biosphere. The goal of safeguards as applied to a GR is to ensure that waste materials under safeguards are emplaced underground as declared by the State and cannot be removed from the GR without being detected.

The *above-ground area* of the GR facility may include infrastructure to support the following activities.

1. Receipt and storage of disposal canisters
2. Transport of disposal canisters to the entrance of a GR
3. Transport of excavated rock from a GR entrance to a location for storage or disposal
4. Transport of backfill material to the entrance of a GR

The *underground portion* of the GR facility may include the following areas and activities:

1. One or more access ramps, excavation shafts, ventilation shafts and monitoring boreholes
2. Excavated and backfilled tunnels with emplacement positions and/or boreholes
3. Receiving and storage areas for equipment, materials, and disposal canister
4. Areas for parking or maintaining equipment used for emplacing disposal canisters and for excavating tunnels and emplacement boreholes
5. Transport and emplacement of disposal canisters
6. Transport of excavated rock to the surface
7. Transport of backfill material from the surface to the excavated tunnels underground

Several different types of shafts may be present at a GR facility. In general, shafts are drilled or mined vertical tunnels that extend from the surface to the underground and are used to house equipment such as lifts, hoists, elevators, ductwork, cables, etc. Shafts may intersect with or connect to other mined features, such as ramps, below the surface.

We develop in this report a model GR based on common features of GR designs from several national programs. In developing our model design for a GR's access points, we assume that DIV inspections are conducted during the construction and operations of a GR and throughout the GR's pre-operational and operational lifetime to confirm the absence of undeclared access points and capabilities for opening disposal canisters underground. We therefore limit our analysis to C/S measures that can detect movements of intact disposal canisters through declared access points.

We focus on surface features and facilities, with special emphasis on those features with access to the underground workings that could provide potential (undeclared) diversion pathways for removing SNF from the emplacement horizon underground. These are (1) the ramp entrance, (2) the excavation shaft entrance, (3) the main elevator entrance, and (4) the ventilation shaft entrance. The first three are considered critical detection points (DPs), whereas the fourth is considered a non-critical DP. The reason for the distinction is due to the different design capabilities of shaft components: the first three (ramp, excavation shaft, main elevator) are all capable of being used to move material from the underground to the surface, whereas the ventilation shaft is not. Thus, we identified four DPs, which we designate DP-1 through DP-4:

DP-1: Ramp entrance

DP-2: Excavation shaft entrance

DP-3: Main elevator entrance

DP-4 (non-critical): Ventilation Shaft

Based on our analysis, we recommend C/S measures for each DP listed above. These are summarized in the following table.

Detection Point	**Access Point**	**Recommended C/S Measures**
DP-1	Ramp Entrance	Video-surveillance camera(s) Portal-monitoring system: • Radiation monitors (gamma & neutron), paired • IR camera(s) • Weighing scale (option) Transport vehicle-mounted MUND
DP-2	Excavation shaft entrance	Video-surveillance camera (triggered) Radiation monitors (gamma & neutron) IR camera (option) Lift-mounted MUND
DP-3	Elevator shaft entrance	Video-surveillance camera (triggered) Radiation monitor (gamma and/or neutron)
DP-4	Ventilation shaft entrances	Video-surveillance camera (triggered) Radiation monitor (gamma and/or neutron)

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
AP	additional protocol
ASTOR	Application of safeguards to repositories (an IAEA expert group)
BMS	balanced magnetic switch
C/S	containment and surveillance
CANDU	Canada deuterium uranium (a type of PHWR)
CoK	continuity of knowledge
CNSC	Canadian Nuclear Safety Commission
CSA	Comprehensive safeguards agreement
DCM	digital camera module
DIQ	Design-information questionnaire
DIV	Design-information verification
DP	Detection point
EOSS	electronic optical sealing system
EURATOM	European Atomic Energy Community
GR	geological repository
HLW	high-level waste
IAEA	International Atomic Energy Agency
IR	infrared
ISSF	integrated safeguards system for the unattended monitoring of SNF transfers
ISVS	integrated safeguards verification system
KBS-3	Term for the Swedish GR design (also used by Finland)
LASSY	laser surveillance system
LCBWS	load cell based weighing system
LILW	low- and intermediate level waste

Abbreviation	Definition
LMCV	laser mapping system for containment verification
MicroGRAND	Miniature gamma ray and neutron detector (2nd generation) (*also* µGRAND)
MiniGRAND	Miniature gamma ray and neutron detector
MMCT	mobile monitoring system for container transport
MUND	mobile unattended neutron detector (*also* mobile unit for neutron detection)
NDA	nondestructive assay
NGSS	next generation surveillance system
NMA	nuclear material accountancy
PHWR	Pressurize heavy-water reactor (e.g., CANDU)
PIDAS	perimeter intrusion detection and assessment system
RDT	remote data transmission
RMSA	remotely monitored sealing array
RRP	Rokkasho Reprocessing Plant
SAR	synthetic aperture radar
SFK	Name for the Swedish GR for SNF
SKB	Swedish Nuclear Fuel and Waste Management Company
SNF	spent nuclear fuel (also “used nuclear fuel”)
UFC	used fuel container (Canada)
VMD	video-motion detection
VPN	virtual private network
WHB	Waste handling building (at WIPP)
WIPP	Waste Isolation Pilot Plant (USA)
YM	Yucca Mountain
µGRAND	MicroGRAND

1. INTRODUCTION

The disposal of spent nuclear fuel (SNF) in geological repositories (GRs) is a new challenge for international nuclear safeguards. Whereas conventional safeguards approaches for other stages of the nuclear fuel cycle rely on nuclear material accountancy (NMA) supplemented by containment and surveillance (C/S), this conventional approach cannot be strictly applied to the disposal process. This is because, unlike conventional safeguards approaches by which NMA can be re-verified if supplementary C/S measures fail, re-verifying NMA of SNF that has been permanently encapsulated in disposal canisters[1] is not realistic, and becomes impossible once disposal canisters have been emplaced in a GR. Maintaining continuity of knowledge (CoK) on encapsulated fuel assemblies will therefore rely on C/S measures to a degree unprecedented in other stages of the nuclear fuel cycle [1, 2].

As emphasized in a recent report by the IAEA expert group, Application of Safeguards to Repositories (ASTOR) [3], access points at a GR present potential diversion paths for nuclear material. Despite the potential for access points to provide diversion pathways, C/S measures for monitoring GR access points have not been examined in detail, and recommendations for effectively applying C/S measures to access points remain to be developed. Given the likelihood that C/S measures will not be implemented underground, a GR and its access points at the surface will require C/S measures that can reliably maintain CoK on SNF buried underground, especially during operations when people, equipment, and materials (both nuclear and non-nuclear) will be regularly entering and leaving a GR.

Access points can include one or more ramp entrances for fuel-emplacement and construction operations (such as waste-rock removal and backfill), personnel and equipment access and egress, elevator and ventilation shafts, and other access points, depending on GR design. Surveillance and monitoring of a GR's declared access points are likely to include video cameras and radiation monitors but could also include complementary or novel methods to increase confidence in CoK, potentially including infrared (IR) cameras, ultrasound imaging, laser-based imaging, mass measurements, and other methodologies or technologies that could detect declared and potentially undeclared material movements between a GR's underground workings and the surface. By using a model GR, we examine and prioritize GR access points and recommend effective C/S options that can maximize confidence in maintining Cok on SNF underground.

1.1. Safeguards Concept

The objective of international safeguards is to deter the spread of nuclear weapons by early detection of misuse of nuclear material or technology, thereby providing credible assurances that States are honoring their international legal obligations. IAEA safeguards are measures through which the IAEA seeks to verify that nuclear material is not diverted from peaceful uses. The IAEA should be able to provide credible assurance not only about declared nuclear material in a State but also about the absence of undeclared material and activities. Under the Additional Protocol (AP), the IAEA is granted expanded rights of access to information and sites. For States with a Comprehensive Safeguards Agreement (CSA), the AP aims to fill gaps in the information reported under CSAs [4, 5].

Overarching IAEA Safeguards objectives at the State level are to detect …

- Diversion of declared nuclear material from peaceful use in declared facilities
- Undeclared production or processing of nuclear material in declared facilities
- Undeclared nuclear material and activities in a state

[1] We use the term 'disposal canister' for the container with SNF that is emplaced in the GR.

The objectives noted above apply to all stages of the nuclear-fuel cycle (some or all of which will apply to a particular State). A GR represents the final stage in the nuclear-fuel cycle, and the IAEA has recommended that safeguards achieve the following objectives for SNF disposed in a GR [6].

- SNF disposed in a GR should be verified nuclear material only by maintaining CoK on verified SNF from the final verification measurement through emplacement in a GR and by maintaining CoK on that GR's containment thereafter.
- Safeguards conclusions that SNF has not been diverted from a GR should provide the same level of assurance regarding non-diversion of nuclear material from peaceful use in all other stages of the nuclear-fuel cycle.
- Safeguards information should be retained for as long as SNF (and other accountable nuclear material) in a GR is under a safeguards agreement (see Section 1.1.1 below).

After the IAEA has verified individual SNF assemblies for partial defects, dual C/S measures[2] will be maintained on verified assemblies from the time they are sealed in disposal canisters, through transfer to a GR, and emplaced underground. Dual C/S will continue to be applied to the GR itself by using effective C/S and monitoring technologies during GR operations, and after closure by using remote-sensing (and/or other suitable) surveillance methods.

SNF transferred to a GR should be verified at the same assurance level required for nuclear material that has been determined by the IAEA to be "difficult-to-access." This will require that dual C/S measures be applied following partial-defect verification [6].

When CoK has been maintained on SNF assemblies through verified, continuous containment provided by a disposal canister, no such canister needs to be re-opened for re-verifying the SNF assemblies inside.

Dual C/S will also need to be maintained on the containment provided by the GR, so that disposal canisters emplaced underground need not be inventoried. The IAEA stipulates that dual C/S applied to a GR be equivalent in strength to that applied to individual disposal canisters.

To provide assurance that a State cannot remove nuclear material from a GR without detection through a declared access route or through an undeclared route, C/S measures should monitor transport vehicles crossing the boundary of the underground GR, monitor other safeguards-relevant access routes, and confirm the continued integrity of containment provided by the restricted zone within the geological formation by detecting mining or other activities that might indicate the construction of undeclared access into a GR (Section 2).

C/S measures installed at a GR facility should operate in unattended mode with remote monitoring capabilities, should function for long periods of time with minimal or no servicing (even in rugged and remote environments), and must meet rigorous system specifications and standards [7].

Geological GR safeguards approaches should provide assurance that nuclear material is not diverted from the above-ground area of the facility or underground GR. To meet safeguards objectives during the life of a GR, safeguards measures should:

- Verify GR design throughout the life of the GR facility (pre-operational, operational, and post-closure phases);
- Maintain CoK on the nuclear material content of disposal canisters;
- Maintain CoK of the nuclear material inventories in the above-ground and in the underground areas of the GR, and
- Detect potential undeclared activities that could be associated with diversion.

---

[2] Dual C/S requires two C/S devices that are functionally independent and are not subject to a common tampering or failure mode [8].

A defined boundary of the underground GR area must be established across which no fuel can cross undetected (Section 2). This boundary includes access points at the surface. If C/S of this boundary meets the standard for dual C/S, the IAEA will not need to know the exact locations of specific canisters (and/or fuel assemblies) within the GR's emplacement areas underground.

1.1.1. Safeguards Information

Most prospective GRs do not include plans to retrieve SNF after it has been emplaced underground, although a few national programs require that retrieval be possible, at least during the operational phase. Nevertheless, any mined GR can be re-mined and SNF could be retrieved if a State is determined to do so; e.g., for safety reasons or a change in national policy. ASTOR has therefore recommended that safeguards-related information be preserved after closure of a GR to cover the potential case for declared retrieval of SNF from the GR. As long as the IAEA exists, the IAEA will upgrade and maintain its safeguards nuclear material databases and retain nuclear material accountancy data associated with all SNF transfers and book inventories, including those transferred into a GR's material balance area.

1.2. Geological Repository Overview

A geological disposal facility has an above-ground area where operational support facilities will be located and an underground area (the GR) where waste will be emplaced for permanent disposal. The underground area is typically planned to be several hundred meters below ground level in a stable geological formation. This is to ensure that waste radionuclides are isolated from the biosphere. The goal of safeguards as applied to a GR is to ensure that waste materials under safeguards are emplaced underground as declared by the State and cannot be removed from the GR without being detected.

The capability to retrieve disposal canisters from a GR is required by law in some States. The geological formation and host rock form a GR's primary containment. The IAEA has defined the "restricted zone" for a GR as "an area surrounding a GR in which no excavations are permitted" (see Section 2)

The *above-ground area* of the GR facility may include infrastructure to support the following activities.

5. Receipt and storage of disposal canisters
6. Transport of disposal canisters to the entrance of a GR
7. Transport of excavated rock from a GR entrance to a location for storage or disposal
8. Transport of backfill material to the entrance of a GR

The *underground portion* of the GR facility may include the following areas and activities:

8. One or more access ramps, access shafts, ventilation shafts and monitoring boreholes;
9. Excavated and backfilled tunnels with emplacement positions and/or boreholes;
10. Receiving and storage areas for equipment, materials, and disposal canister;
11. Areas for parking or maintaining equipment used for emplacing disposal canisters and for excavating tunnels and emplacement boreholes.
12. Transport and emplacement of disposal canisters;
13. Transport of excavated rock materials to the surface;
14. Transport of backfill material from the surface to the excavated tunnels underground.

Several different types of shafts may be present at a GR facility. In general, shafts are drilled or mined vertical tunnels that extend from the surface to the underground and are used to house equipment such as lifts, hoists, elevators, ductwork, cables, etc. Shafts may intersect with or connect to other mined features, such as ramps, below the surface.

This page left blank

2. GEOLOGIC CONTAINMENT: ACCESS POINTS AND THE RESTRICTED ZONE

In the context of safeguards, containment refers to "structural features of a facility, containers, or equipment used to establish the physical integrity of an area or items and can be used to maintain the continuity of knowledge (CoK) of the area or items by preventing undetected access to or movement of material, or interference with the items" [8]. Primarily for safety purposes, a State will establish a "restricted zone" within the geological formation or host rocks surrounding a GR's mined volume through which no mining operations are permitted (Figure 2-1). This restricted zone is then used to formally define a GR's underground containment for safeguards purposes [6, p. 15]. A GR's restricted zone has no sharply delineated boundaries and cannot be visually monitored for penetration in the same way as a room or container for which the IAEA would have access to all exterior surfaces. A GR's restricted zone must therefore be monitored by using remote-monitoring methods (e.g., by geophysical techniques or satellite imagery) in order to detect attempts to breach those declared boundaries. The IAEA and several member-state support programs (MSSPs) have dedicated considerable effort to evaluate remote-sensing methods that can be used to monitor for mining or other excavation activities that could reveal clandestine efforts to breach a GR's restricted zone and gain access to nuclear material in the GR (see Appendix B).

A GR's above-ground containment is provided by the ground surface. Unlike the restricted zone, the above-ground area of a GR includes ramps, shafts, and other access. These access points will be open during a GR's pre-operational and operational phases but closed and sealed upon closure. A GR's access points must be monitored in order to ensure that no nuclear material exits the GR without detection.

Two periods during a GR's lifetime 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 nuclear material will be at the facility during the operational phase only). 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.

During the pre-operational and operational phases, containment will include the ground surface plus the geologic formation (host rocks) within the *restricted zone*, which surrounds the GR on all sides and below (Figure 2-1).

In addition to monitoring for potential breach of the restricted zone, C/S measures during the pre-operational and operational phases will also include restrictions on and detection of movements of nuclear material into (and out of) declared access tunnels and shafts, as well as identifying undeclared activity or unreported access points. Successfully applying such measures requires detailed verification of the GR design (Section 3), knowledge about all operational capabilities underground, as well as the ability to detect undeclared activities. After a GR has ceased operations, C/S measures will be limited to monitoring for (undeclared) attempts to access the GR's emplacement zone through the restricted zone or from the surface above the GR by mining through closed and filled access tunnels and shafts.

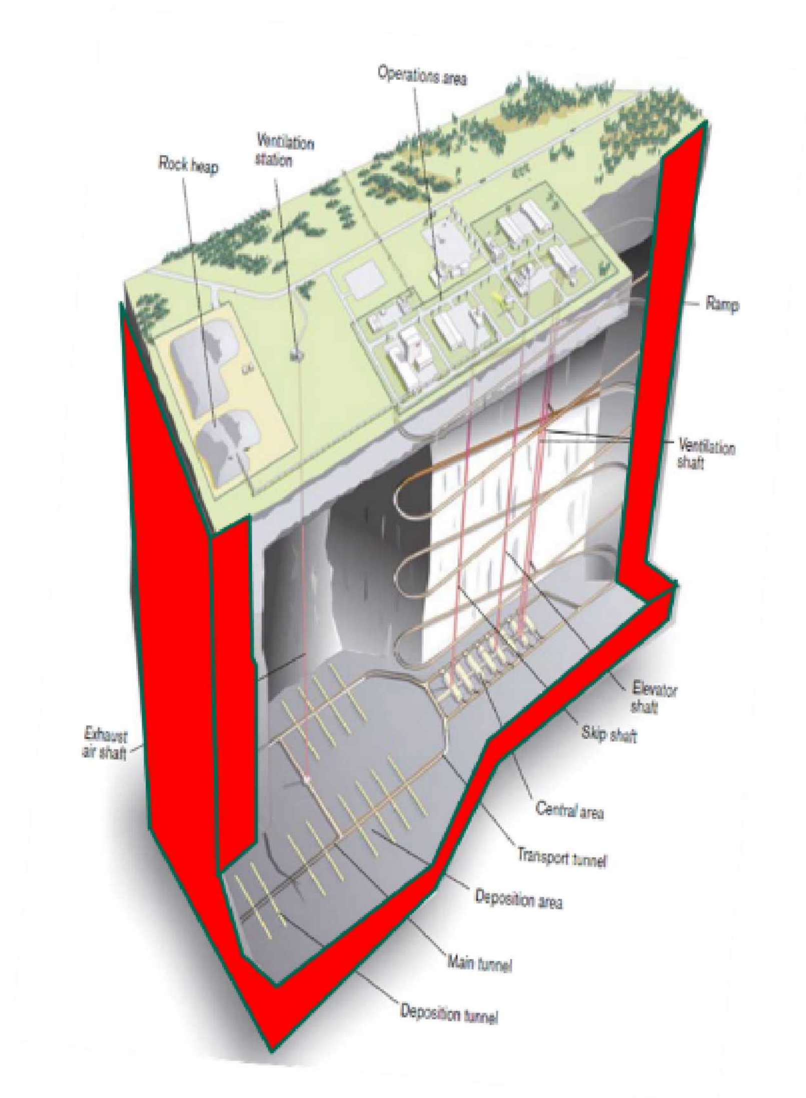

Figure 2-1. Schematic diagram of mined GR volume illustrating the restricted zone (shown in red).

3. DESIGN INFORMATION VERIFICATION

As for any new nuclear facility, the IAEA conducts regular inspections to verify that a GR's design and operations are consistent with those declared by a State in its design information questionnaire (DIQ). The IAEA will conduct design information verification (DIV) inspections during a GR's pre-operational and operating phases in order to (i) confirm the integrity of a GR's (geological) containment, (ii) detect unreported access points, (iii) confirm underground operations, and (iv) detect undeclared areas or activities underground that signify capabilities for (a) removing SNF from disposal canisters or (b) reprocessing SNF.

DIV is used to ensure that the DIQ is correct and complete and that the basis of the diversion path analysis and the associated C/S measures are valid. As the GR design will change during excavation, the application of DIV is envisioned to be a flexible, ongoing process.

DIV of a GR's surface facilities will be implemented primarily through inspector observation of above-ground structures. Declared access points includes surface entrances to ramps, tunnels, excavation shafts, and ventilation shafts, all of which provide access to the underground workings of a GR. Provided that DIV inspections verify that the only access to a GR's underground is via declared access points and that no capabilities to open disposal canisters exist underground, C/S measures used to monitor access points can be limited to being able to detect movements of intact disposal canisters through declared access points

DIV will be the primary safeguards measure to be implemented in the underground area of a GR. DIV should verify that excavation areas are as declared, that there are no undeclared excavations, and should detect any undeclared activities in the GR facility, in the restricted zone that forms the GR's containment, and in the GR's vicinity. During the operational phase, DIV activities will be used to ensure the absence of undeclared underground reprocessing and an assurance of no undeclared operational capability underground for opening disposal canisters. DIV should also confirm the integrity of the GR's restricted area and detect undeclared activities, such as any tunneling in the area surrounding the GR. To accomplish technical objectives (see), DIV may need to use geophysical techniques.

In developing our model design for a GR's surface access points, we assume that DIV inspections are conducted during the construction and operations of a GR and throughout the GR's pre-operational and operational lifetime and confirm the absence of undeclared access points and capabilities for opening disposal canisters underground. We therefore limit our analysis to C/S measures that can detect movements of intact disposal canisters through declared access points.

This page left blank

4. REPOSITORY SURVEILLANCE AND MONITORING

4.1. General requirement

Permanently disposing SNF in a GR is a one-way process: materials emplaced underground will not be retrieved by a State – unless (1) the State reverses its decision to dispose SNF or (2) a safety concern dictates that one or more disposal canisters must be recovered and retrieved. In either case, the State would declare to the IAEA its intent to retrieve disposal canisters containing SNF, and the IAEA would (presumably) verify the retrieval. In the absence of declared retrieval, C/S and monitoring measures maintain CoK on the SNF from encapsulation through emplacement and help provide assurance that SNF that has been transported to and emplaced in a GR facility is not retrieved without detection. The level of assurance provided by such C/S and monitoring measures should meet the technical specifications for an effective dual C/S system as applied to “difficult-to-access” nuclear materials. Spent fuel that is categorized as difficult to access is temporarily relieved from the inventory reverification requirement as long as the implementation of a dual, independent containment and surveillance systems on all credible diversion paths is deemed successful. If SNF that has been determined by the IAEA to be “difficult to access” and dual C/S has been successfully applied, then verifying the C/S system is sufficient for verifying the GR’s physical inventory – without needing to directly verify the GR’s inventory emplaced underground (i.e., SNF).

A GR facility for which an encapsulation plant is located away from the GR (such as the Swedish GR system design) will have an area for buffer storage of disposal canisters in shielding casks that arrive at the GR site from the encapsulation plant. Current thinking is that transportation casks containing disposal canisters would arrive at the GR site with one or more seal that will have been applied at the encapsulation plant.

Buffer storage for a GR might also include an area where empty transportation casks can be stored before being returned to an encapsulation plant. On the (presumably) rare occasions when a disposal canister must be returned to an encapsulation plant for repackaging (e.g., because of damage or other safety concerns), a transportation cask containing a filled disposal canister may also be present in this buffer storage area. Such “reverse” shipments would be declared by the State.

4.2. Safeguards Technical Objectives

IAEA policy paper 15 states that the safeguards system for a GR should be based on (i) verifying design information during the GR’s design, construction and operation; (ii) verifying receipts and flows of nuclear material (SNF) so that nuclear material cannot be removed without detection by any declared or undeclared access routes; and (iii) maintaining CoK on nuclear material content. The IAEA’s general safeguards requirements for a GR system (including the GR, encapsulation plant and transportation) are summarized as follows.

- SNF assemblies should be verified by non-destructive assay (NDA) with high detection probability to detect a partial defect (i.e., confirm that more than 50% of SNF is present). After this verification, each SNF assembly must be maintained under a dual C/S system until sealed in a disposal canister;
- Filled and permanently closed disposal canisters should be maintained under a dual C/S system during storage and transport. Disposal canisters under successful dual C/S are not required to be re-opened for verifying the encapsulated SNF assemblies;
- The GR should be maintained under a dual C/S system as effective as that applied to disposal canisters above ground. Canisters in a GR under successful dual C/S are not required to be verified during a physical inventory taking.

Technical objectives for safeguards at a GR facility are to

- Detect potential undeclared structures or activities that could be associated with diversion, including undeclared cavities and activities in the GR, on the site of the GR, or in the environs of the GR;
- Detect diversion of SNF disposal canisters with or without replacement;
- Detect removal of SNF from disposal canisters received at the GR.
- Detect removal of SNF from disposal canisters in storage and while being transferred underground;
- Detect removal of SNF from the underground areas of the GR.
- Through declared access points
- Ramps, transport shafts/lifts, ventilation shafts, boreholes
- Through undeclared access points
- Covertly constructed or mined tunnels, ramps, shafts, etc.

C/S and other monitoring measures will be used to support these objectives and can support additional safeguards objectives such verifying the receipt and continued presence of disposal canisters at a GR buffer storage area and the transfer of disposal canisters into a GR.

This report primarily addresses bullet 5, verifying that no canisters are removed from a GR through access points, whether declared or undeclared. And while this constitutes the principal role for C/S measures applied to access points, such measures can also help to verify that disposal canisters containing SNF enter the GR as declared.

5. NATIONAL REPOSITORY DESIGNS

The model GR design that we develop in the next section (Section 6) is based on GR designs from countries planning GRs for disposing SNF and other accountable nuclear materials. Prospective designs for GR surface facilities are rarer than those for underground facilities, which severely limits our proposed model GR. Table 5-1 provides the status of several national GR programs with relatively mature GR designs from which we examine those designs that include some level of detail about the GR's surface facilities, which limits us to only a few for our analysis; these are Canada, Finland, Sweden, and the United States. We therefore rely heavily on designs for planned GR surface facilities from these four countries for developing our model GR.

Table 5-1. National Repository Programs

Country	Repository design	Surface facilities described
Belgium	Conceptual	No
Canada	Conceptual	Yes
Finland	Yes (under construction)	Yes (under construction)
France	Conceptual	No
Germany	Conceptual	No
Japan	Conceptual	No
Sweden	Yes	Yes
Switzerland	Conceptual	No
ROK	Conceptual	No
USA		
WIPP*	Yes	Yes (built and operating)
YM	Yes	Yes (provisional)

* Waste Isolation Pilot Plant. Unlike other GR programs listed in Table 5-1, the WIPP is not designed for disposing SNF but is for the disposal of plutonium and other transuranic radionuclides (TRU).

5.1. Canada

Surface facilities in Canada's conceptual GR design include an encapsulation plant, or Spent Fuel Packaging Plant, in which fuel from transport packages will be placed into used fuel containers (UFCs). UFCs will be transferred from the Spent Fuel Packaging Plant to the GR's underground emplacement area via the main shaft complex adjacent to the Spent Fuel Packaging Plant (Figure 5-1). In addition to the Spent Fuel Packaging Plant, Canada's conceptual GR design includes three shaft complexes (main shaft, service shaft, and ventilation shaft), a sealing material compaction plant, and a perimeter fence (Figure 5-1). The ventilation shaft is outside the facility's perimeter fence [9]. The underground facility will be accessible via the three shafts; however, materials from the Sealing Material Compaction Plant and the Spent Fuel Packaging Plant will be transported to (and potentially out of) the underground GR.

The Canadian Nuclear Safety Commission (CNSC) expects safeguards for the Spent Fuel Packaging Plant to be similar to existing safeguards being implemented at CANDU reactors by the IAEA in Canada, which includes instrument-heavy C/S measures, extensive near-real-time information provided by the operator, and short-notice and unannounced inspections.

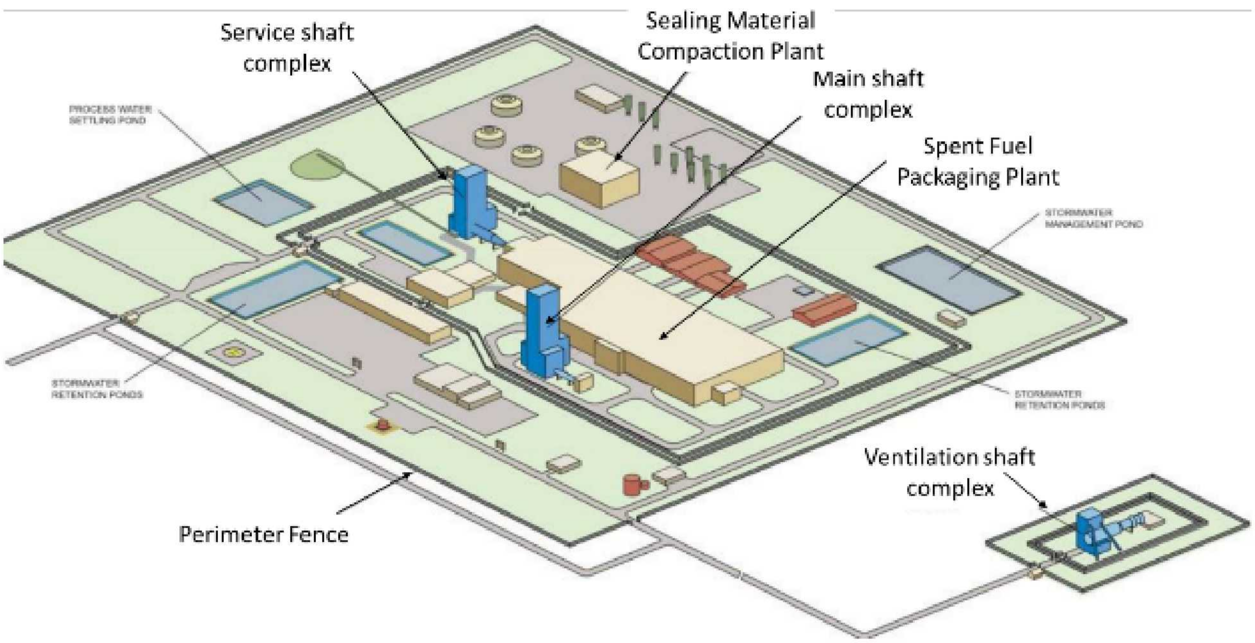

Figure 5-1. Surface Facilities (conceptual design) for Canadian GR. Source: Slide #13 in [9].

5.2. Sweden

Sweden has plans to construct a geological GR for SNF near the town of Forsmark. Sweden's mined GR will be situated some 500 meters below ground; SNF disposal canisters shipped from the encapsulation plant will be emplaced in vertical boreholes using the KBS-3 system, similar in design to that of the Finnish GR.[3] Sweden's GR is designed to have capacity for at least 6,000 disposal canisters (approximately 12,000 tonnes SNF) and will occupy three to four square kilometers approximately 500 meters underground. The only radioactive waste to be disposed at the SFK will be SNF fuel.

Transportation casks containing disposal canisters will be transported via ship on the Baltic Sea from Clink, the combined interim-storage and encapsulation-plant facility, in Oskarshamn to the SFK GR in Forsmark. Following receipt at the GR site, transportation casks will be placed in temporary buffer storage on the surface. Disposal canisters will be removed from transportation casks and disposal canister will be deposited underground at the planned rate of one canister per day.

The ramp entrance is the declared access point through which disposal canisters enter the GR in a shielded cask carried by a transport vehicle for emplacement underground. The ramp leads from the surface to the underground area of the GR. The transport vehicles return the empty casks from underground back to the surface via the ramp.

During the operational phase, the underground workings of the GR will have areas where canisters are being deposited and buffer and backfill are being installed, other areas where new deposition tunnels and boreholes are being constructed, as well as areas where deposition has been completed and tunnels have been sealed (i.e., where canisters have been emplaced and backfill installation has been completed). When all disposal canisters with SNF have been deposited underground, the GR will be backfilled, the surface buildings decommissioned, and the SFK will be permanently closed [10].

[3] In fact, the KBS-3 GR design is a Swedish concept on which the Finnish GR design is based.

Sweden’s GR has equipment to handle and transport disposal canisters and transportation casks, as well as equipment for opening transportation casks and removing disposal canisters from transportation casks. However, no facilities at the GR, neither at the surface nor underground, will have any equipment that could be used to open disposal canisters, extract their contents, or to dismantle fuel assemblies. Any potentially defective disposal canisters that may need to be opened would be returned to the encapsulation plant.

Planned surface facilities at Sweden’s GR near Forsmark are illustrated in Figure 5-2, and a plan view of the prospective surface facilities is shown in Figure 5-3. Table 5-2 lists key surface facilities and their functions.

Figure 5-2. Illustration of prospective surface facilities for the Swedish GR facility at Forsmark. Source: Slide #6 in [11].

Figure 5-3. Plan view of Sweden's prospective GR facility showing surface facilities in relation to underground workings. Note the spiral emplacement ramp and four vertical shafts (two for ventilation, one each for personnel and excavation [skip] shaft); off-site tailings pile not shown. Source: Slide #8 in [11].

Table 5-2. Geological Repository Surface Facilities for Sweden's planned GR site

Facility	Function
Receiving & Buffer Storage	Temporary storage for disposal canisters and transportation casks with room for approximately 10-12 transportation casks (exact capacity to be determined).
Tailings Pile	Surface storage of mine tailings removed from the underground workings of the GR.
Ventilation Station	Fresh-air circulation between underground workings and surface.
Ramp Entrance	Surface entrance to ramp leading to underground workings with access to the underground Receiving Gallery. Disposal canisters will be transported from the surface to the underground via the ramp.
Excavation shaft (skip shaft)	Surface entrance and exit portal for the excavation shaft which connects the inner operation area of the surface facility to the excavation hall in the Central Area underground. The excavation- shaft entrance will be designed to accommodate the movement of rock debris, buffer and backfill materials, as well as electric cables and a diesel-refueling pipe. Current design is for a 5.5-meter diameter shaft to house the rock hoist and other equipment.
Elevator shaft	Two elevators (in the same shaft) will provide transport for personnel and lightweight materials between the surface and the Central Area underground; also route for escape and rescue operations. (6 m dia.)

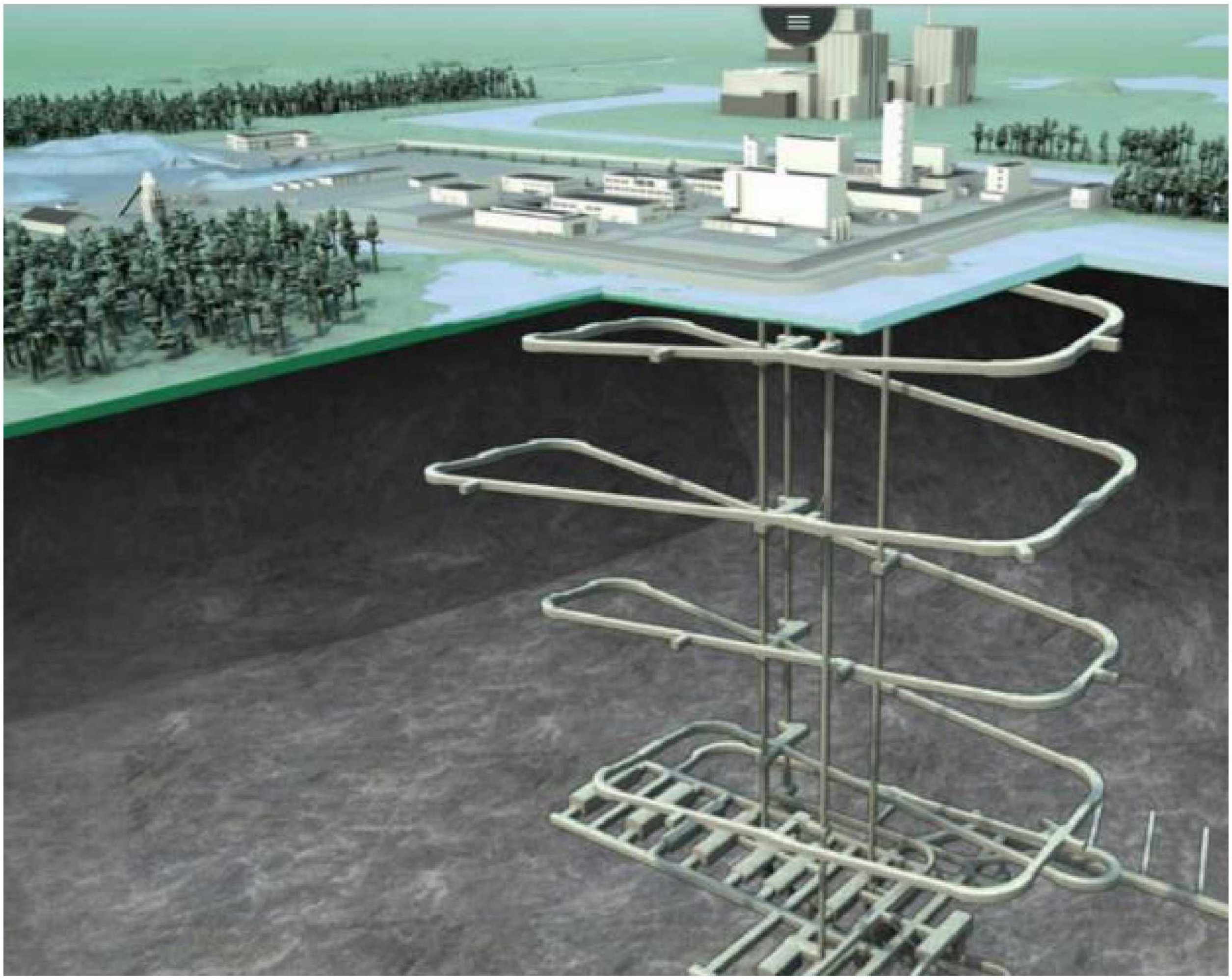

Figure 5-4. Illustration of Sweden's prospective GR facility showing surface facilities in relation to underground workings. Note the spiral emplacement ramp and four vertical shafts (two for ventilation and one each for personnel and excavation [skip] shaft). Vertical shafts connect to the ramp at several subsurface locations. Source: Slide #6 in [11].

The physical relation of surface facilities to underground tunnels, shafts and access ramp are shown in Figure 5-4. One design feature to note in Figure 5-4 is that, like the Finnish GR discussed above, the spiral ramp and vertical shafts intersect at several locations below the surface.

5.3. Finland

Finland is constructing a deep GR near Olkiluoto, Finland . The GR site is close to the Olkiluoto nuclear power plant and an operating low and intermediate-level waste (LILW) repository. Construction began in 2004 on a ramp and an underground rock-characterization laboratory referred to as Onkalo. Onkalo currently comprises an access ramp, shafts for ventilation and hoists, and various niches, tunnels and halls for technical and research purposes. The final disposal facility will include buildings at the surface near the GR entrance, including an SNF encapsulation plant. Other surface facilities at the GR site include buildings for ventilation and hoist equipment (Figure 5-5). A few of these buildings have been completed but most are under construction.

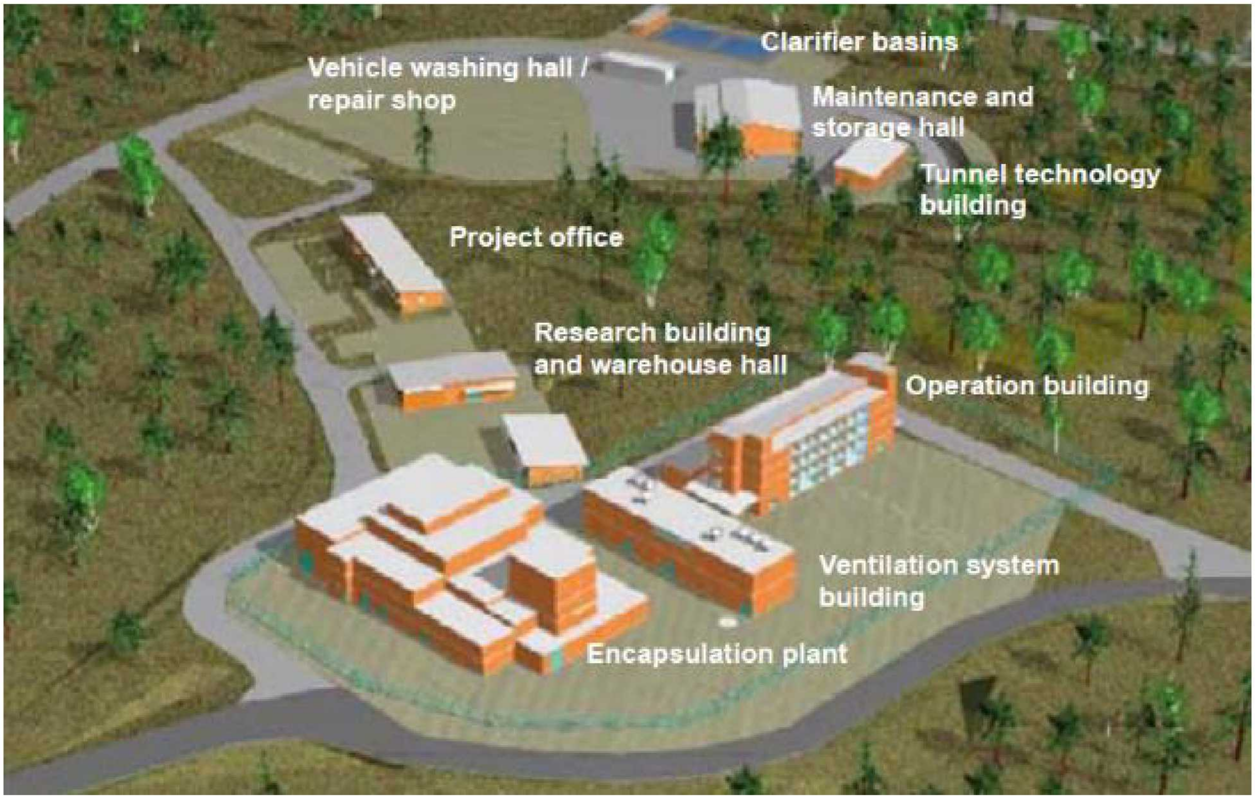

Figure 5-5. Conceptual layout of planned surface structures at Finland's Olkiluoto GR site. Source: Figure 3-1 in [12, p. 47].

The Finnish GR concept and design are based largely on the Swedish KBS-3 design. However, unlike Sweden, which plans for an encapsulation plant to be integrated with its SNF storage facility, Clab, at Oskarshamn, Finland plans to construct its SNF encapsulation plant at the GR site, directly above the GR. Disposal canisters will be lowered directly to the GR's underground area from within the encapsulation plant by means of a hoist/lift. Thus, like Canada, there will be no need to ship disposal canisters from the encapsulation plant to a separate GR.

The encapsulation plant will be built directly over the GR facility. A vertical canister shaft will be the declared access point through which disposal canisters enter the GR for emplacement underground. Canisters will be lowered from the encapsulation plant to the GR emplacement level where they will be received into a shielded transport vehicle. The hoist can also remove a canister from the GR back into the encapsulation plant.

The Onkalo facility's ramp will become the access ramp to the underground disposal facility (Figure 5-6). No disposal galleries have been mined yet, although construction is underway on the GR's central area underground. As illustrated in Figure 5-6, the ramp (Access Tunnel) and vertical shafts intersect at several locations below the surface. The ramp will be used to remove excavated rock from the GR underground to the surface and for transporting backfill and buffer materials from the surface to the underground. As with the Swedish design, the ramp entrance into the Finnish GR is a 5m wide by 5m high access point from the surface to the underground. The ramp is not a declared route for transporting disposal canisters. Filled canisters in shielding casks are expected to weigh more than 25 tons. This will exceed the hauling capabilities of the rock transport trucks (understood to have a maximum payload capacity of 20 tons (e.g., Sandvik TH320 Underground Truck[4]). Shielded transport vehicles are used underground to move disposal canisters from the bottom of the canister shaft to a tunnel for emplacement.

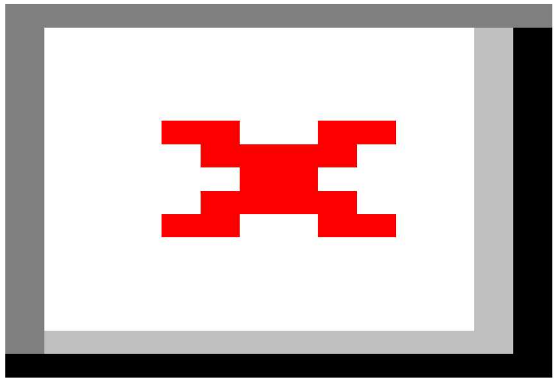

Figure 5-6. Conceptual layout of ramp and vertical shafts (as planned in 2004) at Finland's Olkiluoto GR site (currently referred to as Onkalo). The surface is not shown but is at the top of the image where the Access Tunnel (ramp) ends. Note that the Access Tunnel (ramp) and vertical shafts intersect at several locations. (Emplacement tunnels are not shown but would be at approximately the same level as the Lower Characterisation Level; i.e., approx. -520 m). Source: Figure 2-15 in [13, p. 51].

5.4. USA

The United States has one operating, and one prospective, deep, mined GR. The operating GR is designed for the disposal of defense-related waste, primarily waste contaminated with plutonium and transuranium actinides (TRU). The other, prospective GR is designed for the disposal of commercial SNF is not operating, although some designs and plans for the prospective SNF GR are available. Brief descriptions of these two GRs, emphasizing their surface facilities, are provided in the following sections.

5.4.1. WIPP

The Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico, USA, is a GR for permanent disposal of wastes that contain or are contaminated with uranium and transuranic (U/TRU) wastes, primarily plutonium-contaminated wastes, generated as part of the United States' defense programs. WIPP has been receiving waste since 1999 and represents the world's only operating deep GR for long-lived actinide-bearing wastes (Figure 5-7). Although WIPP is not designed or currently envisioned to receive SNF, WIPP represents the most concrete design of a GR's surface facilities, being currently in

[4] See https://www.rocktechnology.sandvik/en/products/underground-loaders-and-trucks/underground-trucks/th320-underground-truck/ (accessed 29 Oct. 2018).

operation, and provides a robust basis for the design of surface facilities for our model GR (Figure 5-8). The WIPP site is divided into surface structures, shafts, and subsurface structures.

WIPP is designed to receive and handle 510,000 cubic feet per year of waste, both contact-handled waste remotely handled waste. Waste to be disposed underground at WIPP is packaged in waste-disposal containers (most commonly 55-gallon steel drums). Waste containers are shipped to WIPP inside shipping casks (the most common are those called TRUPACTs). Upon arrival at the WIPP site, waste-containing shipping containers are received at the waste handling building (WHB), where the shipping containers are opened and the waste containers removed. Waste containers are then transferred from the surface to the underground through the waste shaft by using the waste shaft conveyance. Surface entry into, and egress from, the waste shaft conveyance and the waste hoist system and their support structures are conducted entirely within the WHB.

There are four shafts at WIPP, the Air Intake, Salt Handling, Waste, and Exhaust shafts. These shafts connect the surface and the underground areas (Figure 5-7) [14]. It is worth emphasizing that WIPP is unique among the GR designs reviewed by us, as it has no ramp leading from the surface to the underground. The underground is accessible only via the four shafts described below.

- The *air intake shaft* is the primary source of intake for underground ventilation.
- The *salt handling shaft* is the means by which mined salt is hoisted to the surface; it also serves as a secondary source of intake air, exhausts air for supplemental ventilation system, and is a route for power, control, and communications cables from the surface to the underground. The supplemental ventilation system draws uncontaminated air upwards through the salt handling shaft. The salt handling shaft extends about 110 feet below the underground disposal level to provide a salt loading pocket and a sump.
- The *waste shaft* provides the only means of lowering waste from the surface to the underground for disposal. The waste shaft is also the air source for ventilating the waste shaft station, and is a route for cables used for power, control, and communications between the surface and the underground. The waste shaft has an auxiliary air intake tunnel to provide additional airflow to the waste shaft station. The waste shaft extends about 118 feet below the underground disposal level to accommodate tail rope dividers, guide rope weights, and a sump.
- The *exhaust shaft* provides exhaust of air from the underground emplacement areas. A metal elbow approximately 14 feet in diameter connects the exhaust shaft to the surface fan ducting.

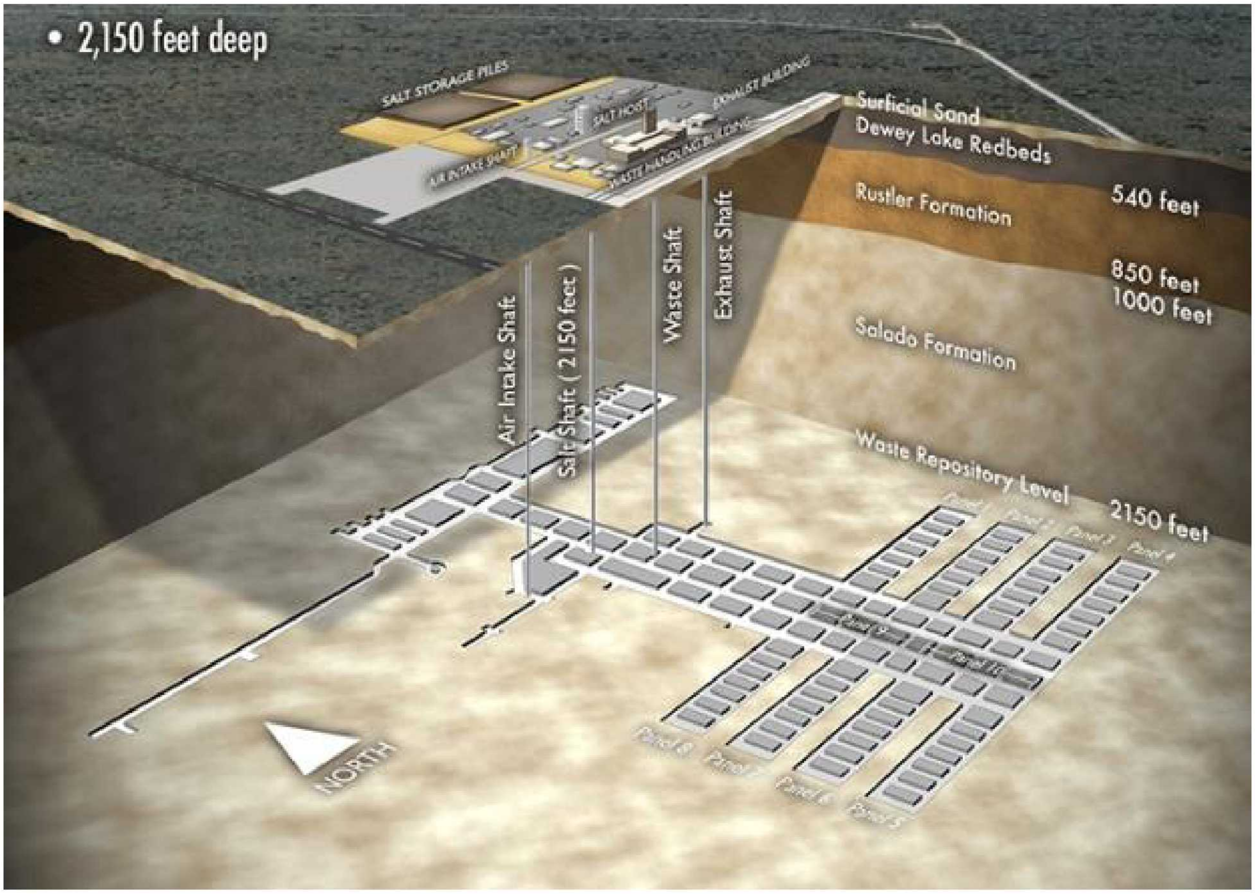

Figure 5-7. Design layout of the WIPP GR showing key surface facilities, waste repository level underground, and vertical shafts between the two. Source: [15].

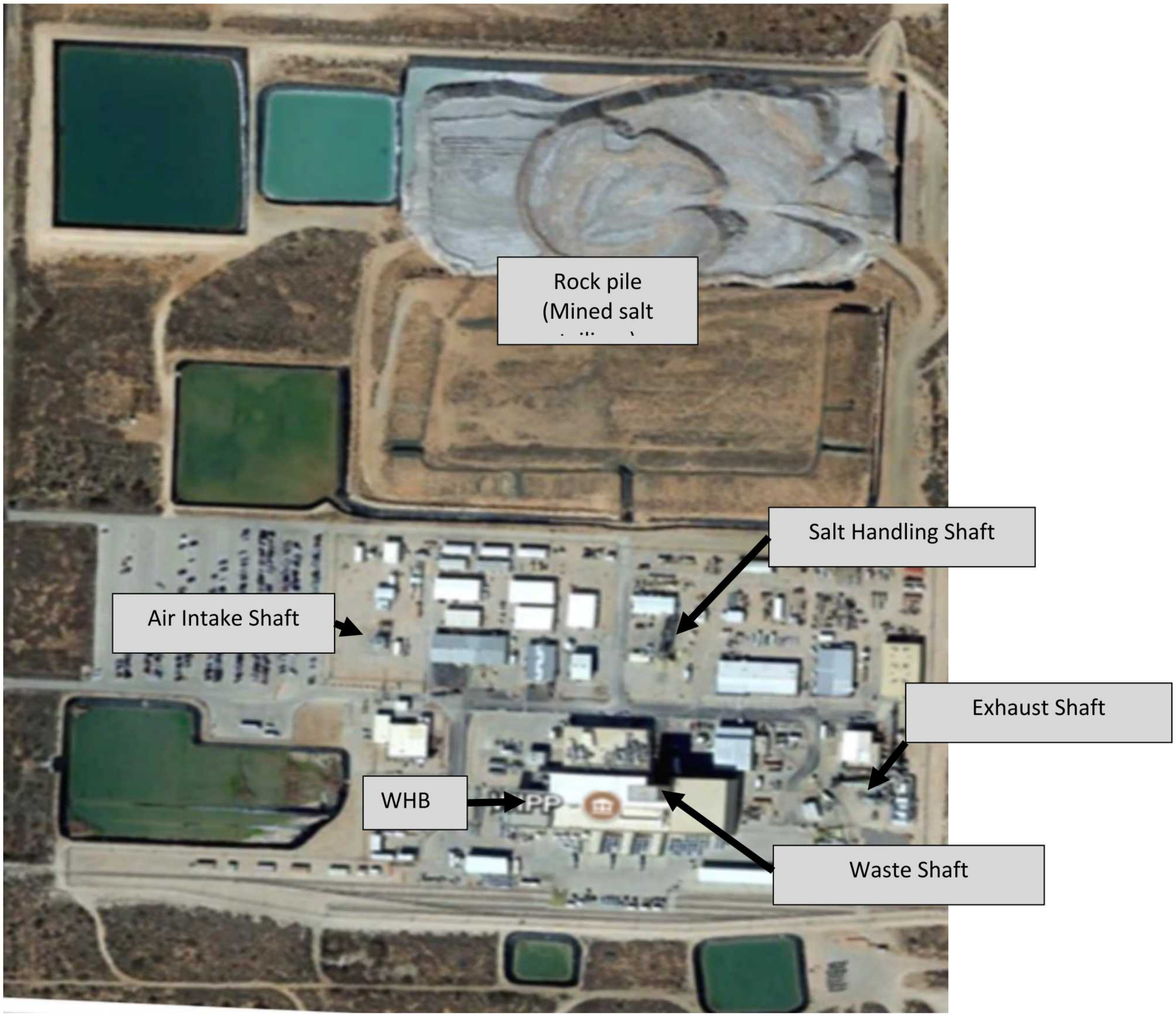

Figure 5-8. Aerial view of surface facilities at the WIPP showing main shaft locations, tailings pile, and waste handling building (WHB). Source: Slide 17 of [16].

5.4.2. Yucca Mountain

Yucca Mountain (YM) in Nevada, USA, is the designated GR site for commercial SNF in the United States [17]. The design of the YM surface facility is among the more mature designs among national programs that provide GR design information. Even so, details about potential surface facilities are not concrete and can differ among documents that describe the YM GR. Information about the YM design reviewed in this section is taken primarily from the *Yucca Mountain Science and Engineering Report* [18].

YM is unusual among GR designs that we examined for this report, in that YM has two ramp entrances, one at the North Portal Repository Operations Area and one at the South Portal Development Area (Figure 5-9). No other GR design that we reviewed has more than one ramp entrance.

Surface facilities in the YM design would be located (1) the North Portal Repository Operations Area, (2) the South Portal Development Area, and (3) the Surface Shaft Areas. All waste receipt and handling operations would be conducted at the North Portal area in the Waste Handling Building (WHB).

The WHB at YM would receive, prepare, and package waste for emplacement underground. All waste-handling operations would use remotely operated equipment. Thick concrete walls, air locks, and access to controlled areas would use techniques to protect workers from radiation exposure. The WHB would house all systems necessary to prepare waste for emplacement. Plan views of the prospective surface site (Figure 5-9) and potential surface facilities (Figure 5-10) at the YM GR are shown below.

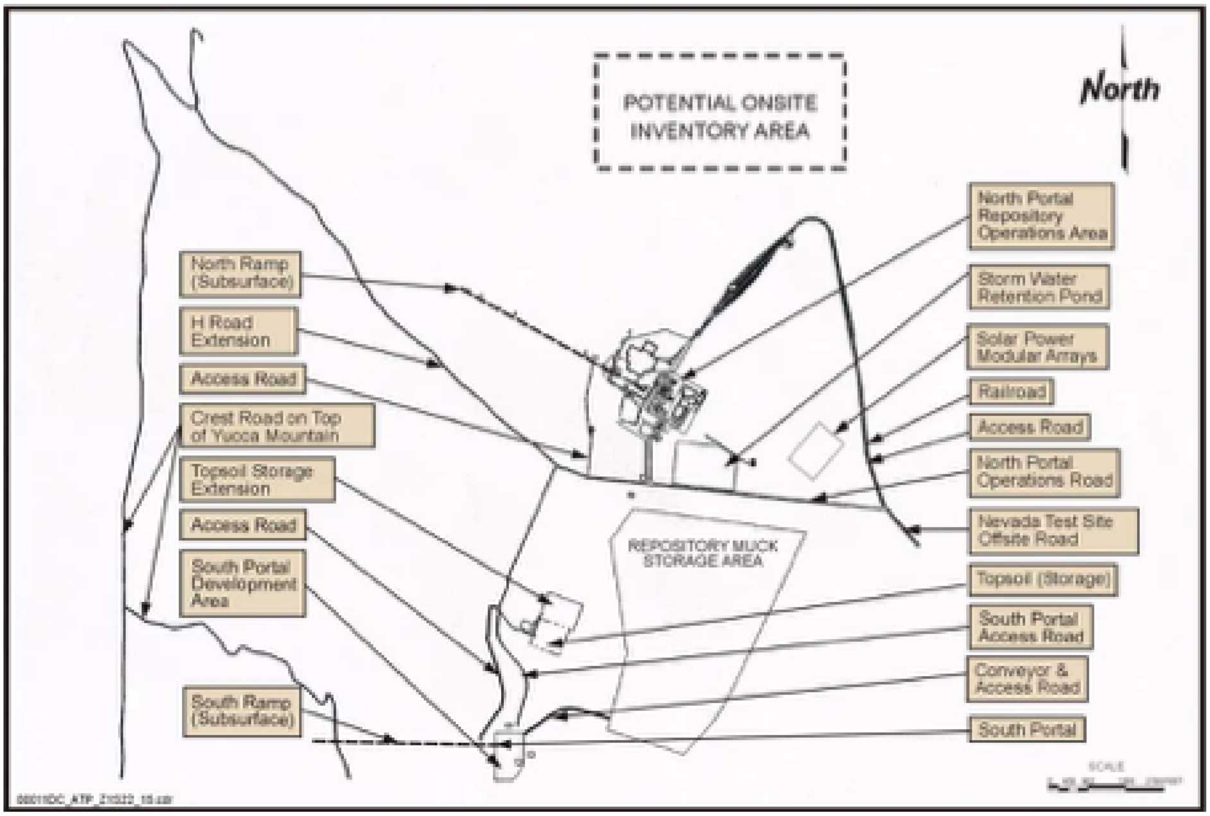

Figure 5-9. Plan view of proposed surface facilities at the Yucca Mountain site. Surface facilities would be developed to support operations and construction activities at portals for the North and South ramps. Roadways would link the two ramp portals. Source: Figure 2-16: of [19].

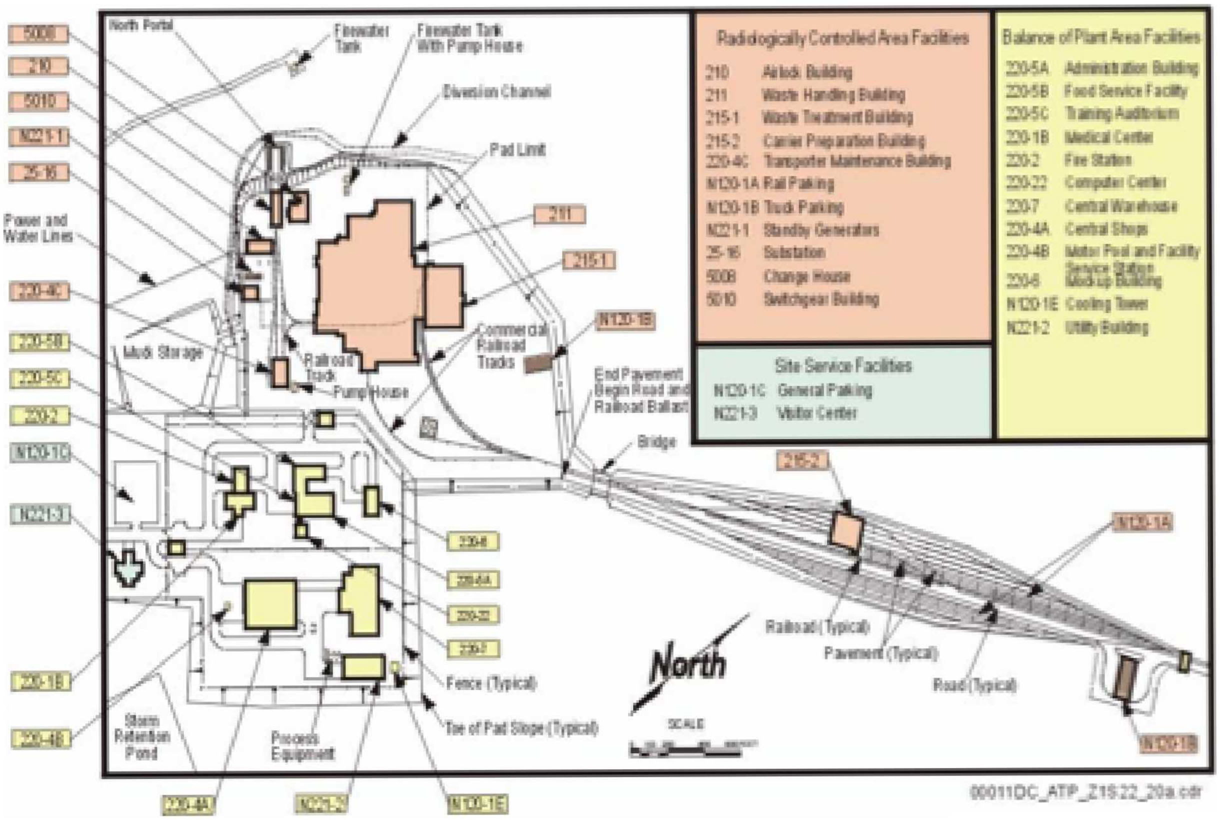

Figure 5-10. Conceptual layout of surface facilities for the Yucca Mountain GR site. Source [19].

This page left blank

6. DEVELOPMENT OF A MODEL REPOSITORY DESIGN

Referring to critical common elements among GR designs reviewed in Section 5 above, along with select elements of the reference GR design described in the IAEA's document, "Model Integrated Safeguards Approach for a Geological Repository" [6], we develop a generic design for surface facilities at a model (hypothetical) GR. By referring to the model's surface facilities and how they are used and potential interact during operations, we develop, in Section 7, C/S options that can provide a high degree of confidence that disposal canisters cannot be removed without detection from a GR's underground workings after they have been emplaced underground.

In developing our model GR design, we make the following assumptions.

- Model GR is designed and operated <u>as declared</u> by the State
  - Verified through DIV inspections
- Model GR has no capabilities or equipment to
  - Open disposal canisters
  - Disassemble SNF assemblies
  - Remove SNF pins from fuel assemblies
  - Reprocess SNF to recover plutonium

These assumptions are predicated on the IAEA conducting DIV inspections during construction and operation of a GR (*cf.* Section 3). Given these assumptions, C/S measures for the model GR are designed to detect movements of intact disposal canisters only. That is, there is no need to monitor for individual assemblies or pins, for example, or for separated nuclear materials obtained through reprocessing of SNF. Such capabilities are assumed to be verifiably absent from the model GR through DIV inspections. Safeguards measures use to verify a GR's design and detect undeclared features or operations are beyond the scope of this study but are reviewed in 11 and discussed in more detail elsewhere.[5]

6.1. Model Repository Areas and Activities

The zone for nuclear material disposal is usually located several hundred meters below ground level in a stable geological formation that ensures long-term isolation of radionuclides from the biosphere. The capability to open SNF disposal canisters in the GR facility is not included in the design of any GR facility on which States have provided information to the Agency.

The GR facility includes an above-ground area and an underground [emplacement] area (the GR proper). This study examines methods for monitoring access to and from the underground area from the above ground area. Because a GR will be under construction for much of its operational phase (including excavation and backfilling), the underground area will continually change over time. Video surveillance systems underground would therefore require frequent installation of new cameras, re-arrangement or re-installation of existing cameras, and possible abandonment of others. On the other hand, declared surface access points, such as ramp entrances and shaft openings, once established, are unlikely to change during a GR's lifecycle. Therefore, this study focuses on applying safeguards techniques to these surface components; i.e., access points at the surface.

The above-ground area of the model GR facility include the following areas and activities (*cf.* reference [6]).

---

[5] For discussions about such measures, see *Technologies Potentially Useful for Safeguarding Geological Repositories* [3]

Areas:

1. Reception area for shielded transportation casks (also called overpacks) containing filled disposal canisters;
2. Temporary (buffer) storage area(s) for disposal canisters;
3. Shaft, ramp, and ventilation-equipment buildings;
4. Mine-tailings pile for excavated rock; and
5. Buildings related to administration, security, and maintenance.

Activities:

1. Receipt and storage of disposal canisters;
2. Transport of disposal canisters from the storage area (buffer storage) to the entrance of the GR;
3. Transport of excavated rock from below ground to a location on the surface or storage (for later backfill underground) or disposal.
4. Transport of backfill material to the entrance of the GR; and

6.2. Model GR access points

We focus on surface features and facilities, with special emphasis on those features with access to the underground workings that could provide potential (undeclared) diversion pathways for removing SNF from the emplacement horizon underground. These and related features and structures are illustrated in Figure 6-1 and described in the sections below; they are summarized in Table 6-1.

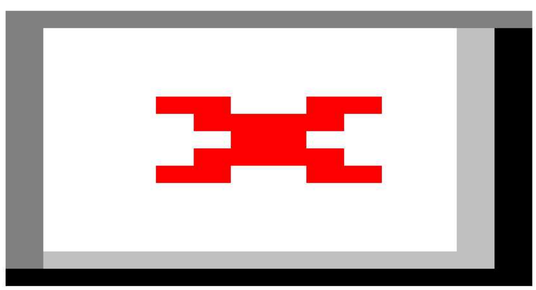

Figure 6-1. Schematic plan-view representation of surface structures of a model GR used for this study. Structures (rectangles) with dashed and shaded circles represent access points between the surface and the GR's underground. The perimeter limits access to the GR facility to authorized equipment and personnel only. Boxes labeled "A.C." indicate access control through the perimeter for authorized ingress and egress (e.g., gates). Arrows show flow directions for disposal canisters ("Receipt") and rock waste. Potential undeclared flows are not shown.

6.2.1. Spent fuel receiving and buffer storage

The receiving and buffer-storage facility is where disposal canisters that have newly arrived at the GR (from an off-site encapsulation plant) are kept until they are ready for emplacement underground. It is the last monitorable stationary location above ground in which disposal canisters can be accounted for, and on which C/S can be maintained (until the canisters are moved). In addition, the buffer-storage area might temporarily house defective disposal canisters that have been removed from the GR and are awaiting transport off-site. The buffer-storage area does not provide access to the GR's underground; that is, it is not an access point. When disposal canisters are ready to be emplaced, they are moved from the buffer storage to the ramp entrance.

6.2.2. Ramp Entrance

The ramp entrance is the declared access point through which canisters enter the GR for emplacement underground. The ramp leads from the surface to the underground workings of the GR. Empty transportation casks returning from underground to the surface via the ramp would need to be verified as being empty before exiting the ramp entrance. Disposal canisters that must be returned to the surface for safety reasons (e.g., damage and other safety concerns) will be rare, but such "reverse" movement would be accommodated and declared in advance.

6.2.3. Excavation shaft (skip shaft)

The excavation shaft is used to move mined rock debris from the GR underground to the tailings pile; it is also used to transport buffer and backfill materials between the surface and underground; it might also be used to house equipment for use underground (e.g., electric cables, refueling pipes). The excavation shaft must lift mined rock debris, and so is assumed for the model GR to be capable of hoisting an intact disposal canister to the surface (approximately 25-tonne hoisting capacity).

6.2.4. Ventilation shaft(s)

One or more ventilation shafts are used to circulate fresh-air from the surface through the underground workings of the GR. Entry points for these shafts are inside a building (or buildings) that houses the ventilation station. Ventilation shafts will not be equipped with lifts or elevators, as confirmed through periodic DIV inspections.

6.2.5. Elevator Shaft Entrance

The elevator is used to transport personnel and small equipment from the surface to the underground workings. One elevator shaft is envisioned, which may contain one or two elevators. The elevators will have capacity to hoist people and equipment, but is insufficient to hoist an intact disposal canister. Declared load capacities for such elevators are verified through periodic DIV inspections.

6.2.6. Tailings pile and conveyor

Underground drifts, tunnels and boreholes will continue to be constructed while disposal canisters are being emplaced underground; that is, during the GR's operational phase. Mined rock debris is hauled to the surface via the excavation shaft and transported via conveyor to a tailings pile (sometimes referred to as the "rock heap") outside the security perimeter (Figure 6-1). As drifts and tunnels underground reach capacity, some of the mined rock is returned to the underground to be used as backfill for some of the filled tunnels.

Table 6-1. Model Repository Surface Features and Access Points

Facility	Function
Receiving & Buffer Storage	Transportation casks containing disposal canisters will be received and stored in the buffer-storage area until each disposal canister is ready to be emplaced. Design verification assures no undeclared access to the GR from the receiving and buffer storage areas.
Ventilation Station and ventilation shafts	Provides fresh-air circulation between underground workings and the surface. Two shafts supply fresh air to, and exhaust air from, the underground. The ventilation station at the surface houses ventilation equipment. Shafts may contain additional equipment (e.g., electric cables, diesel supply lines).
Ramp Entrance & Ramp	Ramp is used to transport disposal canisters from the surface to the underground during GR operations; ramp entrance is at the surface. Transportation casks or other vehicles used to transport canisters down the ramp will return (empty) to the surface via the ramp. Safeguards seals on transportation casks are verified and removed under surveillance before moving disposal canisters underground.
Excavation shaft entrance & shaft	Connects the operations area at the surface to an excavation staging area underground. The excavation-shaft must accommodate the movement of rock debris (tailings) excavated during GR construction, as well as buffer and backfill materials to be moved underground.
Elevator shaft entrance	One or more elevators provide transport for personnel (and small materials) between the surface and the underground. Each elevator shaft will have room for one or two elevators.
Tailings Pile (mined rock waste)	Surface storage of mine tailings (crushed rock waste) that has been removed from the underground workings of the GR via the excavation shaft is transported to the tailings pile by a conveyor or a suitable vehicle. The tailings pile is outside the GR's perimeter. Design verification assures no undeclared access to the GR from the tailings pile.
Perimeter & Access Control	A security perimeter, erected by the State/operator limits access to the surface area of the GR facility to authorized equipment and personnel only though access-control (A.C.) points (e.g., gates). Access-control points include personnel entrance(s), gateways for transportation casks (entering with disposal canisters and exiting empty), and passage of rock waste (tailings) from the excavation shaft to the tailings pile. Design verification, remote monitoring (e.g., passive acoustic-seismic monitors and satellite imagery) and periodic site inspections assure no undeclared access to the GR's underground from outside the perimeter.
Administration buildings	Administration buildings include building and other structures used for a variety of purposes, including maintenance, operations, security, laboratories, equipment storage, and other similar uses. Administrative buildings do not handle SNF, casks or disposal canisters. Design verification assures no undeclared access to the GR's underground from administration, personnel, or other buildings, and that all surface buildings are built and operated as declared (e.g., absence of undeclared reprocessing capabilities).

6.3. Operational components

6.3.1. Surface Operations

Emplacing disposal canisters underground is the crucial operation for a GR; however, a variety of operations will occur at the surface, including temporary storage of as-received canisters, maintenance, movement of personnel and equipment, and mining and other construction-related activities (e.g., rock removal). Many of these operations require access between the surface and the underground and are of potential safeguards concern because each access point corresponds to a potential diversion pathway.

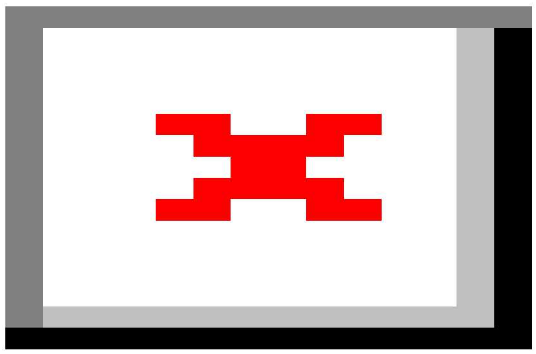

Figure 6-2. Schematic cross-sectional model GR operations (cf. Table 6-1 and Figure 6-1). Horizontal arrows show flow directions at the surface for disposal canisters (left) and rock waste (right), and vertical arrows show movements of SNF into or out of the GR's underground (emplacement zone), both declared (pointing down) and potential undeclared (pointing up). Shaded arrows indicate potential undeclared diversion pathways. Horizontal arrow at left labelled "T.C. out" shows removal pathway for empty transportation casks (without disposal canisters); vertical dashed lines labelled "P" indicate the GR's Perimeter (cf. Table 6-1 and Figure 6-1).

6.3.1.1. Receiving and Buffer Storage Operations

The receiving and buffer storage area of the GR (Table 1) is where SNF disposal canisters in sealed transportation casks are received after being offloaded from a transportation vehicle (ship, rail or truck). Transportation casks containing disposal canisters are sealed at the point of shipping (e.g., an off-site encapsulation plant). Transport casks with disposal canisters may remain in buffer storage while awaiting emplacement in the GR. Because the number of transportation casks is likely to be limited, any such waiting period is expected to be short. Seals on loaded transportation casks might remain intact while in buffer storage. One or more areas in buffer storage will be used for storing empty transportation casks that will be returned to the shipping point, as well as potential (but rare) reverse shipments of transportation casks that contain disposal canisters that need to be returned for repackaging (e.g., damage or other safety concerns).

6.3.1.2. Emplacement operations

When the operator deems a disposal canister ready for emplacement, the canister is moved from buffer storage to the ramp entrance by means of a dedicated transport vehicle. From the ramp entrance, each disposal canister is transported down the ramp to the GR's underground emplacement area, where the canister is emplaced in a tunnel/drift that will be closed and sealed when the tunnel has reached its design capacity.

6.3.1.3. Mining/construction operations

Excavation of underground workings (emplacement tunnels, drifts, etc.) will continue throughout the facility's lifetime, including during emplacement operations. Waste rock will therefore be moved from the underground to the surface via the excavation shaft (Table 1) and transported to and stored on the tailings pile (Table 1). Waste rock may be moved by vehicles or by a continuously operating conveyor (e.g., belt). The tailings pile in the model GR is outside the perimeter, which requires monitored access control for passage through the perimeter.

6.3.1.4. Backfill operations

Emplacement tunnels and other mined drifts in the GR will be progressively closed and sealed as they are filled with disposal canisters. Backfill materials include engineered clay backfill (e.g., bentonite blocks) and waste rock that has been crushed and returned to the underground from which it was mined. These materials will be delivered to the underground emplacement area via the excavation shaft. Backfill and mining operations can be expected to proceed concurrently.

6.3.1.5. Closure operations

Once the GR has been filled, all remaining open tunnels and drifts, as well as the ramp and all shafts, will be filled and sealed by using waste rock and/or other engineered materials. Equipment within these tunnels, shafts, and drifts (e.g., ventilation ducts, mechanical equipment, elevators, etc.) will be removed before they are backfilled. Final closure of the GR will include removing all buildings and other structures on the surface. All C/S safeguards equipment at the surface will be also removed when the GR access points are closed, filled and sealed, and the buffer storage area has been emptied and removed.

6.3.2. *Unusual Design Features*

A few GR designs that we examined for our study include design features that we did not include in our model. None of these features provide access points in addition to those already considered in our model; however, they can complicate the safeguards approach, most commonly by adding on-site capabilities for opening disposal canisters. A few of these are described below.

- ***GR facilities that dispose multiple types of waste***: Some national repository programs plan to dispose wastes in addition to SNF. One such program is the French repository program, which will be designed to take high-level waste (HLW) from SNF reprocessing as well as class B and C LILW. Many such wastes do not contain appreciable amounts of nuclear material but commonly emit high levels of radiation, primarily gamma. Our model GR does not include handling or disposing of non-SNF wastes.
- ***Co-located (on-site) encapsulation plant***: Some facilities, such as the Finnish and Canadian GRs, plan to locate their SNF encapsulation plants at the GR site among the surface facilities. In the case of Finland's encapsulation plant, access to the GR will be provided by a lift inside the encapsulation plant's handling cell that will transport filled disposal canisters directly to the GR's underground for emplacement. This does not represent an additional access point compared wo our model, which includes transport access for delivering disposal canisters to the GR underground. However, an on-site encapsulation plant provides on-site capability to open

disposal canisters and remove SNF assemblies, thereby complicating the safeguards approach for our model GR. Furthermore, encapsulation-plant safeguards are treated separately from GR safeguards by the IAEA, an approach we have also taken in our analysis. Therefore, our model GR does not include an on-site encapsulation plant.

- ***Waste package remediation***: If a disposal canister is discovered to be defective or performing poorly, the waste must be removed from the defective disposal canister and repackaged. Although largely conceptual, some facility designs include the capability to remediate defective disposal canisters, commonly by replacing defective disposal canisters with new disposal canisters. This operation would occur at the waste package remediation facility, which could be located either on the emplacement level or on the surface. Such a facility would increase safeguards and C/S requirements by having tools and machinery on site that can to open waste packages and remove fuel. This capability is similar to that provided by an on-site encapsulation plant (above). Our model GR does not include this capability.

6.4. Component interfaces and interactions

The flow of SNF into the model GR is designed to be unidirectional, from receipt to emplacement underground (Section 6.3). Disposal canisters arrive at the GR in shielded transportation casks. These enter the GR site through a perimeter access point and are delivered to the buffer storage area. Each disposal canister is off-loaded from its transportation cask and stored in the buffer storage area until the disposal canister is ready for disposal. When deemed ready for disposal, a disposal canister is moved out of buffer storage and transported to the entrance ramp on a purpose-built transport vehicle with a shielded cask. The disposal canister passes through the ramp entrance and is taken down the ramp to the underground emplacement area. After unloading the disposal canister underground, the transport vehicle and empty shielded cask (i.e., without disposal canister) returns to the surface and passes through the ramp entrance to the surface. Based on these criteria, we examine interfaces and interconnections between and among various access points and the corresponding below-ground ramps and shafts, as well potential interaction among the associated operations.

Of special note is that most or even all vertical shafts intersect the access ramp in all GR designs that we examined except for WIPP in the USA, which has no access ramp. With this in mind, our model GR also allows for underground connections between shafts and ramp. This means that transport vehicles carrying disposal canisters on the ramp (in either direction, up or down) could conceivably transfer a canister to a shaft that has a lift with sufficient capacity to hoist a disposal canister.

Among the various shafts (main elevator shaft, ventilation shafts, and excavation shaft), none is designed to transport disposal canisters between the surface and underground. Of these, only the excavation shaft, used to hoist mined rock, is likely to have lifting capacity sufficient to bring a filled disposal canister to the surface.[6] For this reason, the same level of C/S implemented at the ramp entrance to assure that no disposal canister passes through that entrance undeclared must also apply to the excavation-shaft entrance.

The only other shaft with a lift is in the main elevator shaft, with a lifting capacity sufficient for personnel and small equipment, but presumably below that required to lift an approximately 24-tonne disposal canister, but which would need to be verified through DIV inspections.

These interconnections are summarized in Table 6-2.

---

[6] 25 tonnes of mined rock would occupy a volume of 20 to 35 cubic meters, based on a rock density of 2500 kg/m^3 and a packing density between 30% and 50%. This is within the volumetric capacity of a hoist installed within the 5.5-meter diameter skip shaft in Sweden's design (Table 5-2) used a basis for the excavation shaft of our model GR.

Table 6-2. Interconnections between shafts and ramp

	Main Elevator shaft	Ventilation shafts	Excavation shaft
Ramp entrance	Yes	Yes	Yes
Main Elevator shaft		No	No
Ventilation shafts			No

* Some national GR designs show ventilation shafts separate from the ramp; however, our model GR assumes all shafts are connected to the ramp below ground, as for most GR designs that we evaluated (Section 5).

6.5. Locations for C/S Monitoring: Detection Points

The objective of C/S measures is to detect both declared and undeclared movements of SNF from the underground emplacement area to the surface and beyond the GR's surface boundary, as defined by the State's security perimeter (labelled "P" Figure 6-2).

By using the model GR, its access point (Section 6.2), operations (Section 6.3) and interconnections (6.4), our study reveals potential undeclared diversion pathways passing through access points at the surface. The access points where these pathways intersect the surface are identified as critical detection points (DP). Three critical and one non-critical DP have been identified from the analysis above and are summarized below.

DP-1: Ramp entrance

DP-2: Excavation shaft entrance

DP-3: Main elevator entrance

DP-4 (non-critical): Ventilation Shaft

6.5.1. Ramp Entrance (DP-1)

The ramp entrance is the declared access point through which canisters enter the GR for emplacement underground. The ramp leads from the surface to the underground workings of the GR. Empty transportation casks returning from underground to the surface via the ramp would need to be verified as empty before exiting the ramp entrance. Disposal canisters that must be returned to the surface for safety reasons (e.g., damage and other safety concerns) will be rare, but must be accommodated.

6.5.2. Excavation shaft (DP-2)

The excavation shaft is used to move mined rock debris from the GR underground to the tailings pile; it is also used to transport buffer and backfill materials from the surface to the underground and may also be used to house equipment for use underground (e.g., electric cables, refueling pipes).

6.5.3. Elevator Shaft Entrance (DP-3)

The elevator is used to transport personnel and small equipment from the surface to the underground workings. One elevator shaft is envisioned, which may contain one or two elevators. The lifting capacity of the lift(s) in the elevator shaft are not designed with lifting capacity sufficient to lift an approximately 24-tonne disposal canister (Section 6.4), as verified through DIV inspections. Lacking sufficient lifting capacity, the main elevator shaft entrance would not need the same level of C/S as for the ramp and excavation-shaft entrances, if any C/S at all. However, assuring that the main elevator's lifting capacity is and remains below that required to hoist a disposal canister to the surface would need periodic DIV inspections at intervals sufficient to ensure that no design changes could be made (and reversed) between inspections. Thus, a heightened level of assurance against undeclared diversion via this pathway might recommend C/S measures comparable to those implemented at the entrances to the ramp and excavation shaft.

6.5.4. *Non-critical Detection Point: Ventilation Shaft (DP-4)*

One or more ventilation shafts are used to circulate fresh-air from the surface through the underground workings of the GR. Entry points for these shafts are inside buildings (or a single building) that house ventilation stations, commonly an air intake and an air exhaust in separate buildings. Ventilation shafts will not be equipped with lifts or elevators, as confirmed through periodic DIV inspections.

The ventilation shaft entrance is not a "critical" DP and therefore does not warrant the same level of C/S monitoring as for the three critical DPs described above. Nevertheless, some level of C/S is justified for the simple reason that the ventilation shaft provides access to and from the model GR"s underground. Caution and conservatism recommends that this access point be monitored for potential diversion concomitant with the level of risk that it presents as a point through which a potential diversion pathway might pass.

6.5.5. *Other Surface Features without Access Points*

6.5.5.1. Spent fuel receiving and buffer storage

The buffer-storage area does not provide access to the model GR's underground and is not an access point. However, the buffer-storage area is where canisters that have newly arrived at the GR are kept until they are ready for emplacement underground. The buffer storage area where C/S can be maintained on *stationary* disposal canisters (until they are moved for emplacement). It is likely (and recommended) that disposal canisters in buffer storage be monitored with effective C/S measures. These might include one or more of the following: a seal on each disposal canister in storage, a seal at the entrance/exit of the storage building, video surveillance of canister inside the storage building and radiation monitors. One reason for this level of C/S reflects the potentially complex uses of the buffer storage area to include newly arrived disposal canisters, empty transportation casks returning to the encapsulation plant, and potentially defective (filled) disposal canisters to be returned to the encapsulation plant for repackaging.

6.5.5.2. Tailings pile and conveyor

Underground drifts, tunnels and boreholes will continue to be mined (and backfilled) while disposal canisters are being emplaced underground. Mined rock debris will be hauled to the surface via the excavation shaft (DP-2) and stored at a tailings pile on site but outside the security perimeter (Figure 6-1 & Figure 6-2). The tailings pile does not provide (declared) access to the underground and mined rock debris is moved from the excavation-shaft entrance (DP-2) to the tailings pile by using a conveyor belt that passes through the perimeter (Figure 6-2). If a diverted disposal canister were to successfully pass C/S measures in place at the excavation-shaft entrance (DP-2), the canister would (potentially) be moved along the conveyor to the tailings pile. A conservative, redundant C/S approach might include one or more C/S measures implemented along the conveyer and/or at the perimeter through which the conveyor passes on the way to the tailings pile.

6.5.5.3. Security Perimeter Access Control

The security perimeter is designed to ensure site security by means of a perimeter intrusion detection and assessment system (PIDAS). Assuring site security a State's responsibility and a PIDAS is not a safeguards-suitable containment structure. Nevertheless, being able to monitor when and where disposal canisters pass through the PIDAS could prove useful for safeguards purposes if only to help corroborate other C/S measures inside the GR site.

6.5.5.4. Administration Buildings

No C/S measured are envisioned for the administration buildings. Such buildings are not designed to provide access to the underground, as verified by periodic DIV inspections (Table 6-1).

7. C/S OPTIONS

The primary safeguards objective of assuring that, once emplaced underground, SNF and other nuclear materials under safeguards remain underground in the GR, is achieved though C/S measures.[7] This section reviews C/S options for monitoring access points for the model GR developed here. These options are summarized in Table 7-1.

7.1. Ramp Entrance (DP-1)

The ramp entrance is perhaps the most important of the three critical DPs, as it is the principle access point through which disposal canisters enter (and potentially exit) the GR. Of key importance is verifying that transportation casks returning from underground to the surface via the ramp are empty before exiting the ramp entrance. Such verification can be accomplished by installing at the ramp entrance a portal-monitoring system that includes paired (directional) radiation monitors (both gamma and neutron) and possibly one or more IR cameras[8]. A weighing scale at the ramp entrance is also recommended, as it can provide additional assurance that transportation casks returned to the surface are empty. The portal-monitoring system might also include surveillance cameras. In fact, video cameras might be in use if operator-managed seals for transportation casks are used [20].

An attractive alternative complementary to monitoring the ramp entrance is to place a MUND detector on each transport vehicle to verify when the vehicle is carrying SNF; this could be combined with a vehicle-mounted video-surveillance camera observing the cask and MUND. A similar system is used for moving SNF to storage at two Argentinian reactors [21] (see Section A.2.6). Such a system would complement but not replace the portal monitoring system at the ramp entrance, although it might simplify the portal monitoring system somewhat, depending on how the systems are designed to interact (if at all).

On presumably rare occasions, disposal canisters might have to be returned to the surface for safety reasons. These would pass through the portal-monitoring system at the ramp entrance, where they would be verified to contain SNF assemblies – as declared by the State. Such compromised disposal canisters would be returned to the buffer storage area to await return shipment to the encapsulation plant.

7.2. Excavation Shaft (DP-2)

The excavation shaft is used to transport large masses of mined rock debris (tailings) from areas under construction below ground to the tailings pile at the surface and will have lifting capacity sufficient to hoist an intact disposal canister to the surface. Furthermore, the excavation shaft intersects the ramp below ground and is a potential diversion pathway, as noted in Section 6.4. For this reason, C/S measures comparable to those employed for the ramp entrance (DP-1) are recommended to be implemented at the excavation-shaft entrance, including radiation monitors and video surveillance. The combined use of gamma, neutron and IR detectors might readily detect disposal canisters hidden within rock debris, although such an application would need to be performance tested. Mass measurements are not recommended, as they cannot distinguish between rock and non-rock loads. A video-surveillance camera might be installed and be triggered if one or more radiation monitors alarms.

Similar to the application noted above, placing a MUND detector on the rock lift might be an effective way to help ensure that the lift is not carrying SNF. If the MUND were to alarm, it could trigger a video-

---

[7] If a State decides to retrieve SNF after it has been emplaced underground, e.g., for safety reasons, the State declares those plans to the IAEA.

[8] IR cameras image heat emissions and could be used to detect unexplained heat emanating from a purportedly empty transport vehicle returning to the surface.

surveillance camera at the shaft entrance. Periodic inspections of the lift and MUND should verify that the system is working properly and not been tampered with.

7.3. Elevator Shaft Entrance (DP-3)

The absence of capabilities below ground to open casks, verified through DIV inspections, helps to ensure that neither isolated assemblies nor their components can be removed via shafts with lifting capacities less than the mass of an intact disposal canister (approximately 24 tonnes). The main elevator shaft is not designed to hoist such loads and may not warrant the same level of C/S as implemented at D-1 and DP-2 (Section 6.5.3). On the other hand, the elevator shaft intersects the ramp below ground and is therefore a potential diversion pathway if some means of hoisting a disposal canister to the surface were devised. Therefore, for added, redundant assurance against undeclared diversion going undetected via this access point, C/S measures comparable to, though more limited than, those implemented at the entrance to the excavation shaft might be used, primarily combined gamma and neutron detectors. Mass measurements are not recommended, as they cannot distinguish between rock and non-rock loads, nor are IR cameras/detectors, as they provide little added value for this DP. A video-surveillance camera might installed and be triggered if one or more radiation monitors alarms

7.4. Ventilation Shaft (DP-4)

The ventilation-shaft entrance is a non-critical DP, as the ventilation shaft has no designed lifting capacity whatsoever (Section 6.5.4). However, it is an access point and the ventilation shaft, like all shafts, intersects the ramp below ground, so that minimal C/S measures might be implemented at this DP. Such minimal measures could be limited to a radiation monitor (gamma and neutron) installed at the top of the shaft, along with a video-surveillance camera that is triggered when the monitor alarms.

7.5. Other Surface Features

7.5.1. Tailings pile and conveyor

If a diverted disposal canister were to successfully pass C/S measures in place at the excavation-shaft entrance (DP-2), the canister could be moved along the conveyor to the tailings pile. A conservative, redundant C/S approach might include one or more C/S measures implemented along the conveyer and/or at the perimeter through which the conveyor passes on the way to the tailings pile. For example, installing radiation detectors (e.g., a MUND) along the conveyor carrying waste rock to the tailings pile could act as an additional C/S measure redundant to those implemented at the excavation-shaft entrance (DP-2).

7.5.2. Spent fuel receiving and buffer storage

Although not an access point, C/S measures are recommended for the buffer-storage area because it can house multiple disposal canisters as well as other items such as transportation casks. Recommended C/S measures for the buffer storage area include video surveillance and radiation monitoring (e.g., neutron monitoring of disposal canisters by using a MUND [mobile unit for neutron detection]). IR cameras could be installed in the area where empty transportation casks are kept awaiting return to the encapsulation plant. Such cameras could detect unexplained heat emanating from casks.

The buffer storage could also be placed under seal by using active electronic seals that can record opening, closing, and tampering, transmitting such information to a local receiving station or via a secure connection to the inspectorate; e.g., the electronic optical sealing system (EOSS) or remotely monitored sealing array (RMSA). Seals may remain on individual transportation casks until each disposal canister is to be removed for emplacement, in which case an active seal in the buffer-storage area might be superfluous.

7.5.3. Security Perimeter Access Control

For the purposes of this report, we do not recommend specific surveillance or monitoring measures for the security perimeter. As noted above (Section 6.5.5.4), the security perimeter is not a suitable containment barrier for safeguards purposes, but could serve as a kind of auxiliary monitoring system to help corroborate C/S measures used at access points in the GR site. Placing radiation detectors or mass-measuring scales at access-control points along the security perimeter could enhance confidence in detecting (undeclared) movements of nuclear material through the security perimeter. Detecting such movements could provide additional information to be used in conjunction with C/S measures and records of movements into and out of the GR.

7.5.4. Administration Buildings

Administration buildings, including buildings for security and other personnel as well as equipment storage do not provide access to the underground, as verified by DIV inspections. No C/S measures are recommended for these buildings, only periodic DIV inspections to assure that they are built and used as declared.

Table 7-1. C/S Options for GR Access Points and Other Features

Detection Point	Access Point	C/S Options
DP-1	Ramp Entrance	Video-surveillance camera(s) Portal-monitoring system: • Radiation monitors (gamma & neutron), paired • IR camera(s) • Weighing scale Transport vehicle-mounted MUND
DP-2	Excavation shaft entrance	Video-surveillance camera (triggered) Radiation monitors (gamma & neutron) IR camera Lift-mounted MUND
DP-3	Elevator shaft entrance	Video-surveillance camera (triggered) Radiation monitor (gamma and/or neutron)
DP-4	Ventilation shaft entrance	Video-surveillance camera (triggered) Radiation monitor (gamma and/or neutron)
*	Tailings Pile & Rock Conveyor	None recommended, but MUND on conveyor as redundant and complementary to DP-2 C/S
*	Buffer Storage	Seals (active and/or passive) Video-surveillance cameras Radiation monitors (MUND at each canister station) IR camera(s)
*	Security Perimeter	None recommended. (*potential option*: radiation detectors and/or scales at access-control points to complement other C/S measures)
*	Administration buildings	None recommended.

* These features are not access points and are therefore not designated DPs.

This page left blank

8. SUMMARY AND RECOMMENDATIONS

Effective monitoring systems will be crucial during GR operations when people, equipment, and materials (both nuclear and non-nuclear) will be regularly entering and leaving a GR. Access points at a GR, such as ramp entrances and shaft openings, present potential diversion paths for disposal canisters. The model GR design analyzed for this study has four declared access points leading from a GR's surface to the underground area (*cf*. Figure 6-1):

1. Ramp entrance
2. Excavation shaft entrance
3. Main elevator entrance.
4. Ventilation shaft entrances

These will be declared in the design information questionnaire and verified during DIV inspections and are unlikely to change during a GR's lifecycle. Three of these four points are identified to be critical DPs (Section 6.5): the ramp entrance (DP-1); the excavation shaft entrance (DP-2); and the main elevator shaft entrance (DP-3). Ventilation shaft entrances are deemed non-critical DPs, as effective DIV inspections should ensure that ventilation shafts cannot be used as diversion pathways. Recommended safeguards measures for all four DPs are summarized in Table 8-1.

Table 8-1. Recommended C/S Measures for Detection Points

Detection Point	Access Point	Recommended C/S Measures
DP-1	Ramp Entrance	Video-surveillance camera(s) Portal-monitoring system: • Radiation monitors (gamma & neutron), paired • IR camera(s) • Weighing scale (option) Transport vehicle-mounted MUND
DP-2	Excavation shaft entrance	Video-surveillance camera (triggered) Radiation monitors (gamma & neutron) IR camera (option) Lift-mounted MUND
DP-3	Elevator shaft entrance	Video-surveillance camera (triggered) Radiation monitor (gamma and/or neutron)
DP-4	Ventilation shaft entrances	Video-surveillance camera (triggered) Radiation monitor (gamma and/or neutron)

This page left blank

REFERENCES

[1] G. Baldwin, R. Haddal and R. J. Finch, "Containment and Surveillance as a Primary Approach for Safeguarding Geological Repositories," in *Annual Meeting of the Institute for Nuclear Materials Management, July 25-28, 2016*, Atlanta, Georgia, 2016.

[2] R. Mongiello, R. J. Finch and G. Baldwin, "Safeguards Approaches for Geological Repositories: Status and Gap Analysis," Sandia National Laboratories, Albuquerque, 2013.

[3] IAEA, "Technologies Potentially Useful for Safeguarding Geological Repositories," International Atomic Energy Agency, Vienna, 2017.

[4] IAEA, "INFCIRC/153 (corrected) The Structure and Contents of Agreements Between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons," International Atomic Energy Agency, Vienna, 1972.

[5] IAEA, "INFCIRC/540 (Corrected) Model Protocol Additional to the Agreement(s) between State(s) and the IAEA for the Application of Safeguards," International Atomic Energy Agency, Vienna, 1998.

[6] IAEA, "Model Integrated Safeguards Approach for a Geological Repository," International Atomic Energy Agency, Vienna, 2010.

[7] B. W. Moran, R. J. Finch and S. J. Tobin, "Design Requirements for Safeguards Technologies Applicable to Safeguards (draft) Y-PM-18-147," Consolidated Nuclear Security, LLC, Oak Ridge, TN, 2018.

[8] IAEA, Safeguards Glossary, 2001 Edition ed., vol. International Nuclear Verification Series No. 3, Vienna: International Atomic Energy Agency, 2001.

[9] P. Burton, "Status of Canadian Spent Fuel Management Program," in *ASTOR XIII, April 25-27, 2017*, Vienna, 2017.

[10] SKB, "Design and production of the KBS-3 repository," SKB, Stockholm, 2010.

[11] J. O. Stahl, "Status of the Encapsulation Plant and the Geological Repository in Sweden," in *Annual Meeting of ASTOR Group of Experts*, Mito, Japan, 2017.

[12] Posiva Oy, "Expansion of the Repository for Spent Nuclear Fuel. Environmental Impact Assessment Report (EIA 2008)," Posiva Oy, Eurajoki, 2008.

[13] T. Saanio, T. Kirkkomäki, P. Keto, T. Kukkola and H. Raiko, "Preliminary Design of the Repository. Stage 2," Posiva Oy, Okiluoto, Finland, 2007.

[14] Nuclear Waste Partnership LLC, "Waste Isolation Pilot Plant Documented Safety Analysis (DOE/WIPP 07-3372, REV. 5b)," US Department of Energy, Washington, DC, 2016.

[15] DOE/EM, "Quick Facts About EM's Waste Isolation Pilot Plant," 23 APRIL 2019. [Online]. Available: https://www.energy.gov/em/articles/quick-facts-about-ems-waste-isolation-pilot-plant. [Accessed 25 April 2019].

[16] DOE/EM, "WIPP Town Hall Meeting, August 2018," US Department of Energy, Office of Environmental Management, 2 August 2018. [Online]. Available: https://wipp.energy.gov/library/documents/2018/Compressed_WIPP_Town_Hall_8-2-

19_FINAL.pdf. [Accessed March 2019].

[17] U.S. Department of Energy, "Nuclear Waste Policy Act of 1982 (as amended)," U.S. Department of Energy, March 2004. [Online]. Available: https://www.energy.gov/sites/prod/files/edg/media/nwpa_2004.pdf. [Accessed March 2019].

[18] DOE, "Yucca Mountain Science and Engineering Report (DOE/RW-0539 Rev. 1)," Department of Energy, Washington, DC, 2002.

[19] DOE, "Yucca Mountain Science and Engineering Report (DOE/RW-0539 Rev. 1)," Department of Energy, Washington, DC, 2002.

[20] R. J. Finch, H. A. Smartt and R. Haddal, "Developing Reliable Safeguards Seals for Transportation Casks to be Applied, Verified, and Removed by State Operators," Sandia Technical report SAND2017-11187, Albuquerque, 2017.

[21] L. Machado da Silva, S. Fernández Moreno, G. Renha, A. Bonino, L. Pardo and G. Diaz, "Experience in unattended monitoring systems applied to PHWR reactors in Argentina–Progress Achieved," in *Proceedings of the 58th annual meeting of the Institute for Nuclear Materials Management*, Indian Wells, California, 16-20 July 2017.

[22] V. Sequeira, K. Ng, E. Wolfart, J. G. Gonçalves and D. Hogg, "Automated Reconstruction of 3D Models from Real Environments," *ISPRS Journal of Photogrammetry and Remote Sensing,* vol. 54, pp. 1-22, 1999.

[23] G. Campos and J. G. Gonçalves, "Environment Authentication Using Range Occupancy Grids," Joint Research Center, Ispra, 1993.

[24] IAEA, "Safeguards Techniques and Equipment. 2011 Edition," International Atomic Energy Agency, Vienna, 2011.

[25] M. C. Browne, R. F. Parker, P. A. Santi and R. B. Williams, "Overview of Safeguards Approach for the BN-350 Dry Storage Facility," in *Transactions of the American Nuclear Society*, La Grange, IL, 2006.

[26] IAEA, "Technology Foresight Preliminary Evaluation Report Q4 2015 (version 1, 6 January 2016)," International Atomic Energy Agency, Vienna, 2016.

[27] P. Chare, Y. Lahogue, P. Schwalbach, A. Smejkal and B. Patel, "Safeguards by Design—As Applied to the Sellafield Product and Residue Store (SPRS)," *ESARDA Bulletin,* vol. 46, no. 2011, pp. 72-78, December 2011.

[28] SKB, "Fuel and canister process report for the safety assessment SR-Site," SKB, Stockholm, 2010.

[29] M. L. Garcia, The Design and Evaluation of Physical Protection Systems – 2nd ed, Amsterdam: Butterworth-Heinemann (Elsevier), 2008, p. 351.

APPENDIX A. SURVEILLANCE AND MONITORING TECHNOLOGIES

A.1. SURVEILLANCE

Video surveillance systems placed at surface entrances to ramps and shafts can be used to monitor movements of materials between the underground and surface. Surveillance methods and technologies are discussed in Appendix A. Video and laser surveillance technologies can be used to monitor access points such as ramp and shaft entrances to detect transport of items. Because access points are likely to be in active, daily use throughout a GR's pre-operating and operating phases, surveillance systems, especially video systems, might need to be triggered by motion or radiation events.

A.1.1. Next Generation Surveillance System

The Next Generation Surveillance System (NGSS) provides a complete surveillance infrastructure that combines data from optical images and equipment state-of-health to help draw safeguards-relevant conclusions. Visual evidence of events is recorded and processed in a front-end camera and stored locally or can be transmitted to a data-consolidator unit where data are stored and are, in turn, transmitted via a remote data transmission (RDT) connection (where allowed, depending on security requirements). Surveillance-review software is used to analyze image files with automatic data filtering and preprocessing, facilitating review by safeguards inspectors. The NGSS has a modular infrastructure that facilitates inventory management, the exchange of faulty modules in the field ("plug and play") and system upgrades.

The NGSS is scalable to any number of cameras. It has advanced security features, low power consumption and solid-state storage media, and is considered reliable in harsh environments. Safeguards-sensitive data and parts inside an NGSS are protected by an electronically sealed, tamper-indicating core module that allows third parties to replace and install data storage modules without compromising data authenticity. Intrinsic sealing and advanced data security for the NGSS are provided by public-key cryptography that enable joint use with other inspectorates or States without the need for additional security or authentication measures.

The NGSS can be configured as a single, all-in-one camera system or as a scalable multi-camera system with dedicated, rack-mounted data storage modules for each camera and data processing and power supply. The NGSS also supports trigger signals from other sensors or electronic seals, remote monitoring, high-resolution and full-color images, and records up to one image per second. Lenses can be chosen based on need and include, for example, a fisheye lens with greater than 180° coverage. A single NGSS camera can simultaneously record up to four distinct fields of view and will replace older IAEA systems based on the standard digital camera module (DCM14).

A.1.2. Laser Surveillance Systems

Deflecting a laser beam (e.g., by using a rotating mirror) enables a scanner to promptly acquire distance profiles of the surrounding premises. Alarms are generated by comparing acquired distance measurements with previously acquired references (distance measurement data are organized as profiles for two-dimensional laser surveillance or as "clouds of points" for three-dimensional laser surveillance). The choice of scanner technology depends on the range of distances to be measured. For short distances (less than approximately 150 cm) *laser triangulation* equipment is commonly used and is useful for identifying, verifying or authenticating safeguards seals and labels.

The LMCV (laser-mapping system for containment verification) is an example of laser-triangulation equipment. Wide-scene surveillance requires laser range finders, which are effective for monitoring distances from approximately 1.5 m to 200 m. This section will address laser range finders that can be used for surveillance.

Laser range finders work by using one of two methodologies: pulsed wave, or continuous wave. A pulsed wave laser range finder emits and detects a pulsed laser beam (tens of kilohertz), and distance is determined either by directly measuring time of flight or by converting frequency to distance.

A continuous wave laser range finder emits a continuous, modulated laser beam (either amplitude modulation or frequency modulation) with a reference waveform, and distance is determined from the phase difference (phase shift) between emitted and received laser beams. Phase shift is proportional to distance (to the target). However, the phase shift is periodic, so the distance measurement, or depth of field, is valid for ranges less than one wavelength; this value determines the range finder's ambiguity interval.[9] Absent some ambiguity-resolving mechanism (such as instructions from an operator), depth of field is constrained to be within a single wavelength (one ambiguity interval). There is thus a trade-off between the frequency of the modulating signal and depth accuracy. If higher modulating frequencies are used, better depth resolution is obtained, and if lower modulating frequencies are used a larger depth of field is obtained.

A.1.3. 2D Laser Surveillance

A two-dimensional (2D) laser range finder scans a planar area defined by the scanning angle (typically greater than 90°) and the divergence angle (typically less than 1°). A reference 2D horizontal distance profile is recorded, and changes to this reference profile (outside a given tolerance) will generate an alarm. An object in the instrument's field of view is something detached from the background; that is, the distance of an object to the measuring instrument is readily extracted from the distance profile. Determining an object's configuration involves some processing to determine the object's extremities and depends on the expected object shape and position. The object's extremities are most readily located at pronounced distance discontinuities; e.g.., points where the laser beam "jumps" from an object to a background surface.

2D laser surveillance systems can detect most changes in an area being monitored; however, if a change occurs out of the surveillance plane (above or below), the change might not be detected. This can be addressed by installing multiple 2D laser surveillance systems (with the new systems' viewing planes either parallel to or intersecting the existing laser system's viewing plane). Alternatively, a 3D laser surveillance system can be used.

A.1.4. 3D Laser Surveillance

3D laser surveillance is achieved by deflecting the laser beam in several azimuths and orientations. The system builds up a "cloud" of points representing distances to surfaces within the field of view. This cloud of points provides a spatial representation of the environment being surveyed; that is, all surfaces are represented in the field of view. These data are used to construct a model of the local environment, from which deviations can be determined [22, 23].

A.1.5. Laser Surveillance System

The Laser Surveillance System (LASSY) is a flexible surveillance system based on one or several 2D laser distance sensors. A LASSY installation is hosted by a dedicated analysis application that runs continuously on a standard industrial personal computer. The computer is either kept in a cabinet near a monitored area and connected to sensors via cables or put directly next to each scanner. The 2D laser sensor surveys its surroundings in a plane by using time-of-flight distance measurements and a scanning angle of 190°. The angular divergence, perpendicular to the scanning angle, is 0.25°, providing a spatial

[9] For example, if the ambiguity interval is 5 m, the system cannot distinguish an object at 4 m from one at 9 m (or another object at 13 m).

resolution of about 4 cm for an object 10 m distant. With a measurement rate of around 20 Hz for a full sweep and durable construction, the LASSY is an effective surveillance system.

The LASSY system has a modular software design with three core components: one or more sensors, analyzers, and alarm modules. The sensors deliver readings to the system, the analyzers perform the essential monitoring, and the alarm provider communicates to external devices. Current analyzer modules are used for one of two situations. *Zone monitoring* uses one or more pre-defined zones in two dimensions in which no "trespassing" is allowed; however, outside the defined zone(s) movement will not trigger an alarm. *Containment-monitoring* is applied to a static situation with no (expected) movement. As for video surveillance systems, multiple LASSY sensors observing a space help the system to be used where there might be occlusions, such as pillars, corners, equipment, etc.

For *Containment-monitoring*, the analysis module records sensor readings and deviations from a reference that are greater than a defined uncertainty (typically 10 cm) will trigger an alarm. For areas affected by large natural variations, a complementary analysis can search for objects closer than a reference point but will discard events beyond the reference point.

An alarm (event detection) can trigger any number of devices, including radiation monitors (Appendix A.2) and surveillance cameras such as the NGSS and/or databases. Sensor data can be transferred and permanently stored. By using the dedicated *Review and Control Application*, alarms or events can be re-played together with surveillance videos.

A.2. MONITORING SYSTEMS

A.2.1. Radiation monitors

A radiation monitor could be used to detect an unexpected radiation signal that might be an indicator of a disposal canister in a cask or hidden in waste rock coming to the surface. Radiation detectors could also be used to detect SNF in casks that have been declared to be empty in a GR's cask storage area.

Radiation monitors could be used to trigger surveillance systems (video or laser) that can record unexpected radiation events passing through one of the GR's access points. Directional (paired) radiation monitors could be used to determine the direction of movement of a radiation emitting item between the surface and the underground. Radiation detectors could be arranged in panels that could be placed along the walls, on the ceiling, or in the floor, to detect radiation. Such systems are used to monitor for radioactive contraband in cargo trucks.

Several mobile radiation monitors are used by the IAEA, including the MUND (mobile unattended neutron detector), the MiniGRAND (Miniature Gamma Ray and Neutron Detector), and the MicroGRAND (Miniature Gamma Ray and Neutron Detector) [24].

A.2.2. Mobile Unattended Neutron Detector (MUND)

Of particular interest for monitoring SNF assemblies and disposal canisters is the Mobile Unattended Neutron Detector (MUND).[10] Because of the potential challenge of detecting low levels of gamma-radiation emitted from a disposal canister inside a shielded transportation cask, neutron detection is an effective method for monitoring a cask containing SNF.

The MUND is an all-in-one neutron detection system for data collection and storage that can run on battery power. The unit contains a ^{3}He detector mounted inside a polyethylene moderator slab and integrated with all the supporting electronics inside a single, sealable enclosure. Once installed, the MUND can collect data for more than eight weeks, after which the unit is replaced with a fully charged

[10] Also known as the "Mobile Unit for Neutron Detection."

unit. Alternatively, the MUND can be connected to facility power and a virtual private network (VPN) to enable remote monitoring with data security.

A.2.3. Miniature Gamma Ray and Neutron Detector

The Miniature Gamma Ray and Neutron Detector (MiniGRAND) combines gamma and neutron sensors that support gross-pulse and current-mode detectors and measurements for safeguards monitoring and measurements. The MiniGRAND can operate in unattended or attended mode, is capable of functioning autonomously in the event of a power loss (resident battery operation) or communication outage (built-in battery-backed-up data storage) and has built-in self-diagnostic capabilities.

The MiniGRAND is compatible with unattended monitoring collection software and can be configured as a standalone instrument or integrated into a board stack for use with other detectors, sensors or surveillance systems (e.g., the *Integrated Spent Fuel Verification System* described in the following section). With appropriate components, the MiniGRAND's capabilities can include Ethernet communications, data authentication and encryption, and remote data transmission (e.g., see [20, pp. 21,37]). The MiniGRAND's front panel-emulator program provides user-friendly interface. Although the MiniGRAND instrument can make some energy discrimination using shielding, it cannot measure the energy spectrum of the radiation present. However, this would not be necessary for most SNF monitoring applications.

The MicroGRAND (μGRAND) has been developed as a "next generation" MiniGRAND. Smaller and lower cost, the μGRAND uses less power than the MiniGRAND and contains four pulse-counting channels; current-sensing capabilities might be added (for use with ionization chambers). The μGRAND has the same configurability, autonomous operation and internal storage as the MiniGRAND, as required for use as an unattended and remote monitoring system. The microGRAND can be used anywhere a MiniGRAND would be used for applications that use pulse counting and has been used to monitor the BN-350 dry storage facility in Kazakhstan [25].

A.2.4. Integrated Spent Fuel Verification System

The Integrated Spent Fuel Verification System (ISVS) is used at the Rokkasho Reprocessing Plant (RRP) in Japan to verify the receipt and unloading of spent fuel, to verify that casks leave empty, and to maintain CoK on spent fuel pool inventory. The ISVS at the RRP includes 12 aerial cameras to ensure adequate surveillance coverage of the spent fuel pool plus six underwater cameras to ensure that casks leave the pool empty. Two redundant MiniGRAND detectors monitor neutron and gamma emissions from spent fuel as the fuel moves through transfer canals. The combined emissions and location determines the direction of fuel movement and can also determine irregularities, such as gamma emission without neutron emission. The system is unattended and joint use.

A.2.5. Mobile Monitoring System for Container Transport

The IAEA currently uses a mobile monitoring system for container transport (MMCT) to monitor transfers of spent fuel assemblies by railcar. The MMCT consists of one or more radiation monitors, video surveillance, and geographical positioning system location equipment, plus power management. Radiation sensors detect a spent fuel assembly during loading, transfer and unloading. The detector enclosure contains the detector assembly, which comprises six ^{3}He neutron tubes and two ionization chambers. The system can acquire safeguards data over a continuous period of more than one week under harsh outdoor conditions without recharging the batteries. The MMCT might be modifiable for use as a monitoring system for transporting spent-fuel disposal canisters inside casks although this would need testing and approval.

A.2.6. Integrated Safeguards System for the Unattended Monitoring of Spent Fuel Transfers

The Integrated Safeguards System for the Unattended Monitoring of Spent Fuel Transfers (ISSF) is used to monitor transfers of spent fuel from two Argentina pressurized heavy water reactors (Embalse and Atucha) to dry storage casks [21]. The ISSF combines a MUND and two independent optical-surveillance cameras mounted on the transfer vehicle that moves spent fuel from reactor pools to dry storage in spent fuel transfer flasks. A similar arrangement might be applied to the transport of spent fuel disposal canisters from a reactor to an encapsulation plant or from an encapsulation plant to a GR, potentially including intermediate transfers to and from buffer storage areas.

A.3. OTHER MONITORING SYSTEMS

A.3.1. Heat/Infrared monitors

Recent developments in the field of infrared camera technology and the variety of commercially available systems could prove advantageous to implementing international safeguards at a GR [26]. Infrared cameras could monitor surface portals from the underground to confirm that vehicles exiting the underground are not transporting thermally hot disposal canisters. Infrared cameras could also be used to monitor locations where empty transportation casks and/or empty disposal canisters are stored and transported to confirm that they are empty. The infrared camera needs to detect object whose temperature was 10° C above ambient temperature or 25° C below the expected temperature in the cargo bed of a vehicle. A complicating factor would be that the engine of a transport vehicle will be hot after climbing up from the underground area of a GR.

A.3.2. Weighing Systems

Weight monitors (e.g., load cell-based scales) installed at a GR's entry ports, such as the entrance to a ramp or shaft, can be used to monitor the weight of a transport vehicle or of an elevator carrying disposal canisters from the surface to the underground area and when they return to the surface. Transports should be verified as containing the declared mass of vehicle with disposal canister and a shielded transport cask when entering the GR and returning to the surface with just the empty transport casks; that is, without a disposal canister.[11] The weighing systems could also monitor the weight of rock transports (vehicles or elevator skips) exiting the underground area.

For ramps, an appropriate method for measuring weight could be a truck scale, such as used to measure weights of highway trucks. Although a mature and commercially available technology, these types of scales are not currently used by IAEA for safeguards and would need to be tested and approved for that use. A load sensor on a hoist or elevator could be used to detect weights relevant to a disposal canister on an elevator.

The Load Cell Based Weighing System (LCBWS) is used by the IAEA to determine gross weights of bulky, massive objects, notably nuclear-material items such as of UF_6 containers. The weighing system consists of a load-cell, electronics, and associated hardware. The LCBWS operates in two load ranges: up to 5 tons and up to 20 tons [27]. The load-cell design includes two shackles separated by a load supporting element bonded to a strain gauge. When a load is lifted with a hoist, the strain gauge deforms, changing its electrical resistance. The resistance change is converted into a weight that is displayed on a digital-readout unit attached through a cable to the load cell. Typically, gross weights can be measured with an uncertainty better than 0.1%. The LCBWS might be applied to weighing disposal canisters if the

[11] In special and presumably rare cases, defective loaded disposal canisters might be returned to the surface for safety reasons. These would be declared movements and verified by available means.

capacity of the LCBWS could be increased to handle a filled disposal canister (e.g., 25 to 27 tons for the Swedish copper-canister design) [28].

Several types of truck scales are commercially available that are based on load-cell systems, bending-plate systems, and piezoelectric systems. Load-cell systems are the most common truck-scale technology in use and operate in a fashion like the LCBWS.

- A load cell has one or more strain gauges that transmit an electric current when the cell is subjected to a weight. The wire in the strain gauge is altered or compressed slightly, changing the wire's resistance to current passing through. The signal from each cell is sent to a junction box, where sensors measure the variance in the current and calculate the amount of weight the scale is supporting. Strain gauges in load cells can be either compression or tension based.
- A bending-plate system uses strain gauges attached to metal plates. As weight is applied to the metal plates, the strain gauge on each plate determines the load. In a typical truck scale of this type, the weights from each gauge are added together to get the total for each truck's axle.
- Piezoelectric systems use a series of piezoelectric sensors embedded in a conducting material. When weight is applied, the pressure changes the voltage across the conductor. Sensors measure the change in voltage which can be used to calculate the load. Loads from each sensor are added together.

Truck scales applied to measuring weights of transfer vehicles at a GR's ramp entrance might be one of two common types currently in use.

- *One-stop static scales*. A series of scales are used to weigh an entire truck after it comes to a stop on the scales. Each scale is typically connected to a single electronic controller that automatically combines all axle weights to determine gross weight.
- *Weigh-in-motion vehicle scales*: A series of embedded sensors determine weight per axle as a truck drives over the sensor pad. Unlike the one-stop method, there is no need for the truck to come to a complete stop while being weighed. This would reduce impact on operations somewhat compared to static scales; however, current weigh-in-motion technologies may be less precise and accurate than most static scales. The degree to which WIM scales might be applicable to and acceptable for safeguards purposes would need testing and IAEA approval.

A.3.3. Motion Detectors

Technologies used to detect physical motion are commonly used for security systems (also known as intrusion-detection systems) and include volumetric systems that monitor three dimensions, planar systems that monitor two dimensions, linear systems that monitor in one dimension such as wires and lasers, and switches or vibration sensors that monitor opening and closing of doors, or movement on or cutting of fences, etc.

- *Volumetric sensors* detect movement (energetic or radiative changes) within a volume of space defined by the sensor's field of view and distance from the sensor for which the receiver can detect a signal above background (e.g., radiation intensity falls off with the square of distance between the receiver and a radiative source or reflecting target).
- *Planar sensors* detect changes within a planar geometry typically defined by angles of scanning and divergence of, for example, a laser. Nearly all planar sensors are active IR sensors.[12]

[12] The distinction between volumetric and planar is somewhat arbitrary, as planar sensors detect movement within a narrow volume (e.g., defined by the scan angle and the (perpendicular) divergence of the IR beam, the latter being typically less than one degree).

- *Linear sensors* generally include those sensors attached to fences (e.g., fiber-optic cables) and are not discussed here; however, active infrared sensors are linear sensors designed to detect interruptions in a transmitted and reflected infrared beam caused by an object crossing the beam. Active infrared motion sensors are therefore likely to be useful motion detectors for access points at a GR facility.

Motion sensors are further divided into active and passive systems, depending on whether they emit a signal or electromagnetic radiation (e.g., microwave, infrared, or other electromagnetic) or only collect radiative energy from the environment. Some dual technologies use both. Finally, motion sensors can be divided according to whether they are to be used inside a building (interior sensors) or outside (exterior sensors) [29].

- A passive sensor uses a receiver to detect energy (commonly as emitted radiation) in the monitored environment with the objective of detecting changes due to, for example, an object entering or leaving a monitored region. Passive sensor technologies with potential applications to monitoring at a GR facility include those based on detecting (changes in) heat, light, sound and other mechanical vibration, cable tension, pressure, capacitance, and magnetic and electric fields.
- Active sensors both transmit and receive radiation/energy that can be used to detect changes in the received energy caused by an object entering or moving within the region actively monitored by the transmitted and reflected radiation. Most active sensor technologies include infrared, microwave, and other radio-frequency devices. Ported coaxial cables used to detect changes in an induced magnetic field are also active sensors, as they require an electrical current in the cable. Active devices tend to be less susceptible to false (nuisance) alarms than passive sensors.

Two motion-sensing technologies of special note include video-motion detection (VMD) and balanced magnetic switches. VMD is a passive, volumetric sensor method, in that a camera (the sensor) receives visible light from within the camera's field of view. A VMD system detects a change in a defined region of a scene being viewed by using software to analyze images. VMDs are in common use by the IAEA and could be used to monitor storage areas or other locations where movement is minimal (ventilation shafts), infrequent (excavation portals) or regularly scheduled (emplacement-ramp entrances). VMDs do not work well dim or no-light conditions,

A balanced magnetic switch (BMS) is a type of electromagnetic sensor commonly used to detect the opening of a door or window to which it is attached. When a door or window is opened, the two halves of the BMS separate and an alarm is triggered. A Hall switch, like a BMS, uses electricity to operate by detecting charge separation in a wire caused by a change in magnetic field (the Hall Effect). A Hall switch provides improved tamper and defeat protection over a BMS [29]. A BMS or Hall switch could be used to detect doors and other portal entrances which when opened might be used to trigger a video camera.

This page left blank

APPENDIX B. REMOTE SENSING METHODOLOGIES FOR C/S[13]

B.1. Satellite imagery applied to C/S for GRs

Satellite imagery is a promising method for continual, periodic, and ad-hoc surveillance of a GR's surface facilities and above-ground workings. Satellite imagery that has been considered for monitoring GRs includes microwave, optical (e.g., visual and infra-red cameras) and synthetic aperture radar (SAR).

High-resolution optical and microwave satellite imagery can be used to detect surface changes that deviate from a GR's declared design or layout. Such changes could include surface objects, structures, equipment, or features resulting from construction of or modifications to buildings, roads, and other infrastructure. These changes may be subtle changes in terrain elevation (e.g. rock-waste heaps or excavation piles), new features (construction or infrastructure) or changes in signal characteristics (e.g. vegetation removal, indicating human activity).

Local weather conditions at a GR site may make continuous coverage with commercially available optical data difficult during certain times of the year. Although 'optical' satellites can provide a picture that can be readily interpreted, the availability of useable images acquired during the winter months in the northern latitudes may be limited. Unlike optical remote sensing instruments, SAR sensors operate under almost all-weather conditions and independently of the sunlight, i.e. time of the day or season. If the IAEA were to depend solely on optical sensors, it may experience long periods when it cannot obtain satellite imagery [7].

After a GR is backfilled and sealed, satellite and geophysical monitoring will become the primary techniques for detection. Satellite imagery should be used in combination with geophysical monitoring to provide for remote assessment of indicators of potential undeclared excavations. In addition, satellite imagery could serve as a backup measure to geophysical monitoring when the geophysical monitoring detects a direct signal of a potential excavation. While the IAEA may choose to monitor a GR relatively infrequently (e.g., annually), it may also determine (according to site or State-specific evaluations) that more frequent observations are required.

B.2. Geophysical methods applied to C/S for GRs

Geophysical techniques allow continuous monitoring of structures and activities that take place underground at a distance and are blocked by the surrounding rock from visual observation. Depending on the excitation strength and the size of the sensor array, a range up to several kilometers can be covered. After the operational phase, when a GR will have been closed and everything backfilled, geophysical detection can be used to monitor the volume surrounding the GR for changes and, especially, intrusion attempts. Arrays of sensors, in shallow, as well as deep, boreholes could be used to sense mining activities. In addition to passive seismic and borehole radar, passive electromagnetic systems could also be used to monitor for electromagnetic signals emanating from electronic sources associated with mechanical systems. The detection of construction of undeclared access pathways is an extension of DIV (Section 3).

For accessing a closed underground GR from the surface by a new shaft or from the side by a new ramp or tunnel, three basic excavation techniques can be used: mechanical, hydraulic, and thermal. The latter two could be designed to produce markedly less vibration, but currently are less effective and need development to be effective excavation techniques for excavating a tunnel. The mechanical techniques are established and well known: (i) drilling holes and blasting the rock, which can proceed by meters per day, and (ii) tunnel boring machine, which breaks the rock by mechanical contact over the full cross section, advancing tens of meters per day. Alternatively, by using a chisel or a rock hammer, the cross section is

[13] This appendix taken largely from Sections 6.4 and 6.5 of reference [7].

worked on sequentially, advancing much more slowly. Blasting produces strong seismic signals two or three orders of magnitude greater than that of the tunnel boring machine. In both cases, the debris must be transported away, by a vehicle or a conveyor belt, which is an additional source of seismic excitation.

After the operational phase, when all underground cavities will have been backfilled, aerial or satellite imagery and geophysical techniques are the only unattended technologies that could gain information about potential attempts at getting access to the disposed nuclear material. Whereas seismic sensors could be deployed in open parts of the GR that have not yet been backfilled during the operational phase, after closure no sensors and cables can remain in the underground area because they could create pathways for ground water to enter the GR. Borehole positions for geophysical monitoring would need to be outside the GR boundary.

Signals from sensor arrays can be co-processed to increase the signal-to-noise ratio and to get directional sensitivity. The triggering of an alarm should be performed fully automatically. Because excavation activities to access the underground area of a GR would likely require several months, a time and directional analysis should be integrated in the automated geophysical monitoring analysis system to reduce the false alarm rate to a minimum. To result in an alarm, the excavation would need to be observed to be persistent and moving towards the GR.

B.2.1. Passive Seismic Monitoring

Removal of rock to get access to an underground location exerts time-varying forces on the rock that deform the elastic medium. Passive seismic detection relies on emissions produced when such forces are exerted on the rock, as is done by all kinds of mining activities.

Passive seismic monitoring can be performed from the surface, from boreholes, or from underground installations. For detecting blasting, sensors would not have to be inside the host rock but could be deployed in a netted structure around it. Components in boreholes would observe lower seismic background noise, be more sensitive to the seismic or acoustic sources, and better provide information about source depth.

To find the best possible locations for the seismic sensors, noise sampling campaigns should be carried out before installation of the system to measure the seismic noise at various locations at the surface and at various borehole depths over an extended period. Optimized sensor locations and network design will significantly lower the detection threshold. The amplitude decay of background noise with depth, as measured in the sample boreholes, can be used to decide at what depth the borehole sensors should be installed in order to reach the desired sensitivity level.

Individual seismic or acoustic events will not be a concern as the monitoring system will need to assess patterns of seismic signals. For example, a consistent set of seismic signals that are moving towards the GR or out from the declared GR over time. Thus, randomly occurring seismic events (such as rock cracking as stresses normalize) or vibration sources on the surface (e.g., road construction) should not create a false alarm.

B.2.2. Active Electromagnetic Monitoring

At suitable sites active electromagnetic monitoring can be used as a safeguards technique to detect and localize undeclared underground activities around a GR. A geophysical radar technique has been developed for the exploration of the bedrock, directional borehole radar. Such a monitoring system could establish a ‘shield’ of electromagnetic waves around a GR enabling early detection of activities a sufficient distance from the emplaced nuclear material.

The method provides information about the inner structure of the bedrock. Under best conditions, high penetration depths of hundreds of meters up to kilometers can be achieved. Stationary antennas can provide a high reliability to ensure a long-time operation (e.g., several decades) and high fidelity to prevent false alarms. Borehole radar antennas can be combined to form a network of a radar monitoring system. Such a monitoring system could provide a comprehensive coverage of the space around a GR. In order to provide a shield and enable the localization of possible activities, directional antennas should be used for continuous monitoring. Borehole radar is still in prototype development and testing.

B.2.3. Passive electromagnetic monitoring

Passive electromagnetic monitoring would use antennas similar to those used for active electromagnetic monitoring to detect electromagnetic signals from excavation or operational activities in the environs of a GR. All systems that generate or use electricity emit an electromagnetic field that could be detected. This would include lighting as well as machinery. The feasibility of passive electromagnetic monitoring has not yet been investigated.

This page left blank

DISTRIBUTION

Email—External

Name	Company Email Address	Company Name
Wayne Mei	Wayne.Mei@nnsa.doe.gov	NA-241 Concepts & Approaches

Email—Internal

Name	Org.	Sandia Email Address
Rodney Wilson	6800	rkwilso@sandia.gov
Dianna Blair	6830	dsblair@sandia.gov
Robert Finch	6832	rfinch@sandia.gov
Zoe Gastelum	6832	zgastel@sandia.gov
Tina Hernandez	6832	therna@sandia.gov
Heidi Smartt	6832	hasmart@sandia.gov
Steven Horowitz	6835	shorow@sandia.gov
Evaristo Bonano	8840	ejboban@sandia.gov
Rob Rechard	8842	rprecha@sandia.gov
Ben Cipiti	8845	bbcipit@sandia.gov
Silvia Saltzstein	8845	sjsaltz@sandia.gov
Nathan Shoman	8845	nshoman@sandia.gov
Technical Library	9536	libref@sandia.gov

This page left blank

This page left blank

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.