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Safeguards Implications for Deep Borehole Disposal of Spent Fuel

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Abstract

Deep borehole disposal (DBD) has been suggested as an option for disposing spent nuclear fuel in a number of countries, including several countries that are subject to international safeguards. While potential benefits of deep borehole disposal include increased safety, reduced cost, and greater flexibility, the method could also impact the implementation of international safeguards.

DBD presents some unique safeguards challenges compared to a conventional MGR. These challenges include 1) verifying borehole design below the surface; 2) strong reliance on CoK up to and including disposal; 3) limitations on the ability to observe or verify successfully emplaced canisters; and 4) successfully monitoring a closed and sealed DBD facility over the long term. In some cases, such challenges may prove easier for a DBD facility than for a conventional MGR, others more difficult, and still others may require new methodologies (or existing methodologies newly applied to safeguards). Long-term monitoring in particular might be somewhat less onerous.

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TABLE OF CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

The International Atomic Energy Agency (IAEA) is currently examining safeguards approaches for the disposal of spent nuclear fuel (SNF), including encapsulation plants and conventional mined geological repositories (MGR). Although deep borehole disposal (DBD) has been suggested as an option for disposing spent nuclear fuel in a number of countries, including several countries that are subject to international safeguards, the potential impact on how safeguards applied to DBD might differ from the safeguards approach for a conventional MGR has not been considered in any detail. We examine some of those differences in this report.

When comparing potential safeguards approaches for disposal of SNF in a conventional MGR with possible safeguards approaches for a DBD facility, we find that many aspects of safeguards will likely be similar. A few differences may prove considerably more challenging, while other differences might simplify or even eliminate certain safeguards requirements.

In most regards, the safeguards approach for an encapsulation plant used for encapsulating SNF for a DBD facility should not differ from the approach used for a plant that encapsulates SNF for disposal in a conventional MGR. One potential difference concerns whether a DBD design requires SNF assemblies be dismantled and individual fuel pins consolidated in disposal canisters. Such a design could significantly challenge inventory accountancy and continuity of knowledge (CoK). Should such an approach be taken, a suitable safeguards approach for maintaining CoK on separate fuel pins will need to be developed. We make no suggestions here beyond the need to implement adequate surveillance measures.

No substantive difference is envisioned in applying safeguards during transport of SNF canisters to a DBD facility compared with safeguards measures envisioned for transport of SNF canisters to a conventional MGR. Both types of disposal options require transport casks (aka “overpacks”) to be sealed and probably tracked during shipment.

We find more, and more substantive, differences in potential safeguards approaches for the two kinds of disposal facility: DBD vs. a conventional MGR. Four main safeguards criteria are most affected:

1. Verifying design information
2. Maintaining CoK of nuclear material
3. Verifying receipts and flows
4. Detecting undeclared activities.

Design Information Verification

Conducting design information verification (DIV) for a DBD facility presents few additional complications compared to DIV for a conventional MGR, and in many aspects DIV might be simpler. Drilling multiple boreholes at a single site could lead to more complex demands on DIV than a single-borehole facility, but should still be less demanding than the complex underground workings of a conventional MGR. Verifying that boreholes are drilled and otherwise constructed as designed would likely be done in a manner quite different from that envisioned for DIV for the underground workings of a conventional MGR and might require new or existing equipment that would need to be modified for safeguards use. Such equipment might include conventional equipment currently used for borehole inspection and characterization by the drilling industry. Other equipment might include modifications to existing safeguards monitoring equipment to make it applicable to detecting drilling operations. In most cases, however, existing safeguards technologies or those currently being developed for safeguards applications to conventional MGR should be applicable for DIV of DBD facilities.

Maintaining CoK through effective containment and surveillance measures

For the most part, maintaining CoK on SNF during encapsulation and transportation should not present major differences from the same activities for a conventional MGR. Disposal canisters will be transported from the encapsulation plant to the disposal facility (either DBD or MGR) in purpose-built transport casks that will be sealed with tamper-indicating seals and possibly tracked during transport. However, as noted below, the ability to emplace a canister into a borehole directly from its transport cask is a potential advantage of DBD for maintaining CoK compared with a conventional MGR.

Verifying receipts and flows of SNF

Few differences were identified between disposal concepts when it comes to verifying receipts and flows of SNF. Disposal canisters with SNF will arrive at a DBD facility in much the same manner as disposal canisters will arrive at a conventional MGR. Emplacement of canisters directly from transport casks into the borehole might enhance CoK, as noted.

Detecting undeclared activities

During the operational phase of a DBD facility, most safeguards measures envisioned for a conventional MGR would apply to a DBD facility as well. These include site inspections and environmental monitoring (e.g., for undeclared retrieval or diversion of canisters, and for undeclared activities). One significant difference is the fact that canisters cannot be opened and SNF removed within a borehole. Unlike a conventional MGR with its complex underground workings, underground activities are unlikely at a dedicated DBD facility; that is, on-site clandestine facilities would be separate from the boreholes and might be more readily detected during routine inspections and DIV. One possible complication arises if an empty or “dummy” canister were to be successfully substituted for a full one that has been diverted. In such a case, there might be little or no possibility of discovering the dummy after it has been emplaced down hole. Avoiding such a scenario is best assured through effectively maintaining CoK through containment and surveillance (C/S). The potential benefit of DBD emplacement to maintain CoK was noted above.

Retrievability

Effectively ensuring that no canisters containing SNF are returned to the surface undeclared might be accomplished by using portal radiation monitors and other C/S measures, such as surveillance cameras, at all access points. Unlike a borehole, a mined repository will have multiple access points, including ramps and shafts, potentially making the effective use of portal monitors and other C/S measures more complex for a conventional MGR than for a DBD facility. By contrast, the single point of entry and exit for a DBD facility should simplify the implementation of C/S measures used to detect undeclared recovery of emplaced canisters (e.g., directional radiation monitors). Recovering buried SNF after borehole closure will be difficult;

however, a variety of design considerations, both during operations and after closure, may affect retrieval. Such design considerations might be verifiable before closure, but not afterwards (post-closer access to a borehole would be monitored by methods already under consideration for a conventional MGR).

Long-term monitoring

A closed and sealed DBD facility is likely to be monitored over the long term for potential undeclared activities by using the same methods envisioned for long-term monitoring of a conventional MGR; that is, by periodic site inspections, on-site seismic/acoustic monitoring, and satellite or aerial imagery. Largely because of its depth, several methods that might be used to recover SNF from a conventional MGR after closer cannot be used to recover SNF from a sealed deep borehole (e.g., conventional mining or tunnel-boring machines), so that the need to develop monitoring techniques to detect such activities is obviated. And while drilling might not be as noisy as many conventional mining techniques, potentially making acoustic detection more difficult, the fact that such an operation would require equipment at the surface, might make visual detection easier.

One potential added difficulty of effectively monitoring for undeclared access to SNF disposed in a deep borehole is the surface area around the borehole that might need to be monitored. Because of advances in directional drilling, the area to be monitored might be considerably larger than for a conventional MGR. Whether a deep borehole will require safeguards monitoring for an indeterminate period far into the future may depend on a better understanding about the risks of SNF being recovered from such depths after such a long time so deep underground.

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NOMENCLATURE

Abbreviation	Definition
AP	additional protocol
BWR	boiling water reactor
CoK	continuity of knowledge
C/S	containment and surveillance
DBD	deep borehole disposal
DIV	design information verification
EP	encapsulation plant
HLW	high-level waste
IAEA	International Atomic Energy Agency
KBS-3	reference design for Swedish Repository Concept
KMP	key measurement point
LWR	light water reactor
MGR	mined geological repositories
NDA	non-destructive assay
NMAC	Nuclear Material Accountancy & Control
NPP	nuclear power plant
PIV	physical inventory verification
PWR	pressurized water reactor
SNF	spent nuclear fuel
SRD	shipper-receiver difference
TBM	tunnel boring machine

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1. INTRODUCTION

Disposal of nuclear and radioactive wastes in very deep boreholes (ca. 5 - 3 km depths) has been examined as a possible alternative (or complement) to mined geological disposal. Although all currently planned repositories for permanent disposal of high-level waste (HLW) and spent nuclear fuel (SNF) will be mined, potential technical and cost advantages of deep borehole disposal (DBD) have been examined by several countries. The DBD concept involves drilling a borehole into crystalline basement rock to a depth of about 5,000 m below the surface, emplacing waste canisters containing SNF and/or HLW in the lower 2,000 m of the borehole, and then sealing the upper 3,000 m of the borehole. Each borehole might hold about 400 waste canisters of approximately 5 m length (Arnold B. W., et al., 2011). Multiple boreholes might be constructed at one disposal site, with spacing between boreholes determined by thermal loading. In at least one conceptual design, a borehole seal system comprising compacted bentonite clay and concrete has been proposed to seal the upper 3 km of the borehole (Arnold B. W., et al., 2011; Arnold B. W., et al., 2013).

While the primary benefits of DBD could be increased safety, reduced cost, and greater flexibility (Brady & Driscoll, 2010; Bates, Driscol, Lester, & Arnold, 2014), the method could also impact the implementation of international safeguards. DBD has been suggested as an option for disposing spent nuclear fuel in a number of countries,[1] including the UK (Nirex, 2004), South Korea (Kang, 2014), Sweden (Åhäll, 2006), and the UAE (Al Bloushi, Beeley, Kim, & Lee, 2015). Disposal facilities for spent nuclear fuel and other nuclear materials in the latter three countries (ROK, Sweden, UAE) are subject to international safeguards under their safeguards agreements with the IAEA. With some exceptions (Swahn, 1996; DOE, 1996; von Hippel & Hayes, 2010; Nirex, 2004), few studies mention safeguards considerations for DBD, and none addresses such considerations in much detail. This report attempts to address that gap.

First, a special note about what we mean by “deep borehole” or “very deep borehole.” In the context of disposal for SNF (and other attractive nuclear materials), the term deep borehole should not be confused with emplacement boreholes that are part of the design for some conventional mined geological repositories (MGR), such as the KBS-3 reference repository design for Sweden and Finland (SKB, 2010), or Germany’s reference design for its Gorleben reference repository site (Bollingerfehr, et al., 2013). Neither should “deep boreholes” in the context of spent-fuel or nuclear-waste disposal be confused with the IAEA’s concept of borehole disposal for radioactive sources (IAEA, 2009); these are considerably shallower (30 meters to a few hundred meters) than the 4,000 to 5,000 meters envisioned for deep or very deep boreholes (Arnold B. W., et al., 2011).

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[1] Despite such suggestions, no country has yet decided to pursue DBD of SNF. And while DBD has been suggested as a potential option for the US (Bates, et al. 2014), the US has not selected DBD as a disposal option for commercial SNF (DOE 2014).

2. DISPOSAL SYSTEM

The permanent disposal of SNF and other radioactive wastes generally begins when these materials are declared as waste. Such wastes are most commonly placed into waste-disposal canisters that are then sent to a facility for disposal.[2] Thus, a radioactive waste disposal system typically comprises three primary components: an Encapsulation Plant, where waste is placed into disposal canisters, Transportation, for moving the encapsulated waste, and a disposal facility, which, for purposes of this report, is either a conventional MGR or a DBD facility (no discussion of shallow land burial is included here). We discuss these three components in order, but we consider the disposal facility in particular detail, as this is where MGR and DBD display their greatest differences and are, therefore, expected to most profoundly differ in how safeguards will be implemented.

3. ENCAPSULATION PLANT

The encapsulation plant is where SNF, as either intact assemblies or as consolidated fuel pins (see Appendix A: Deep Borehole Disposal), is placed into disposal canisters that are welded shut. Disposal canisters become items under safeguards at the encapsulation plant, effectively replacing, as items, the spent fuel assemblies that they contain. After they are welded shut, disposal canisters are transported to the disposal facility. Draft model integrated safeguards for encapsulation plants are being developed by the IAEA (IAEA, 2010). In most regards, safeguards for an encapsulation plant should not differ whether disposal is to be via conventional MGR or DBD. In fact, certain aspects might prove easier for DBD; e.g., disposal canisters containing single pressurized water reactor (PWR) assemblies.

Canisters that would be compatible with DBD are envisioned to have smaller diameters and be much less massive than disposal canisters designed for SNF disposal in a conventional MGR. Disposal canisters designed for emplacement in a conventional MGR are on the order of one meter in diameter (SKB, 2010b), whereas the diameters of disposal canisters destined for disposal in a deep borehole are envisioned to be about 35 cm or less (Arnold B. W., et al., 2011; Raiko, Sandström, Rydén, & Johansson, 2010). And at 1.5 to 2.0 tonne per fully loaded borehole disposal canister (Raiko, Sandström, Rydén, & Johansson, 2010), the mass of a fully loaded conventional disposal canister for a conventional MGR will be ten to twenty times greater (25 to 30 tonnes each). Maintaining safeguards and CoK on the smaller DBD canisters should not present special challenges compared to the larger disposal canisters for a conventional MGR.

There is one issue, however, that could complicate safeguards on SNF destined for DBD compared with MGR, and that is the manner in which disposal canisters might be packaged. As described in more detail in the Appendix A: Deep Borehole Disposal, making DBD more cost effective by maximizing the mass of SNF that can be disposed in a single deep borehole has led to suggestions that fuel assemblies be dismantled before encapsulation, with individual fuel pins consolidated into each disposal canister. Such a design could hold 350 or more PWR fuel pins in each

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[2] Certain wastes are disposed without encapsulation; these are not discussed here.

disposal canister, about 30% more than a single PWR assembly (Arnold B. W., et al., 2011). The primary safeguards challenge for such a design would be maintaining inventory accountancy of individual pins after assemblies have been dismantled until such time as a disposal canister is sealed (and the pins no longer visible or accessible). In addition to the dramatic increase in countable items, fuel pins have no unique identification, whereas fuel assemblies do.[3]

It is worth mentioning that some States may face restrictions on dismantling SNF assemblies due to constraints of certain nuclear-cooperation agreements (e.g., some bilateral “123 agreements” with the US prohibit altering US-origin SNF without consent). Other restrictions may apply on SNF assemblies, so that concern about this design option for DBD remains just that: a concern.

4. TRANSPORTATION

The reactor, encapsulation plant, and final repository may be adjacent or widely separated, but will always entail some degree of transport of fuel assemblies (reactor to encapsulation plant) and disposal canisters (encapsulation plant to temporary above-ground “buffer” storage at the disposal facility, and buffer storage to emplacement underground). Safeguards for transport of disposal canisters to a conventional MGR have been discussed elsewhere (Mongiello, Finch, & Baldwin, 2013), and relatively little difference is envisioned in applying safeguards during transport to a DBD facility compared with transport to a conventional MGR.

Disposal canisters destined for a DBD facility would (presumably) be shipped inside of purpose-built transport casks (aka “overpacks”), and these transport casks would be sealed with tamper-indicating seals, as would be done for transport casks containing canisters for disposal in a conventional MGR. Transport casks containing disposal canisters might also be tracked (via satellite for example) during shipment from the EP until delivery at the disposal facility. A DBD facility, as for a conventional MGR, is likely to have a receiving area and buffer storage for transport casks holding disposal canisters awaiting emplacement. Safeguards seals would not be removed from transport casks until the start of the emplacement process (see section on Verifying Receipts and Flows).

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[3] The concern here is for countries subject to international safeguards under an IAEA safeguards agreement. Whether any country will choose this design option for DBD remains to be determined. As noted, the US has chosen not to consider DBD for commercial SNF, nor is it considering disassembling other SNF for potential DBD.

5. REPOSITORY SAFEGUARDS AND DEEP BOREHOLE DISPOSAL

The IAEA has examined safeguards for MGR, and a review of IAEA policy and recommendations for MGRs provides a basis upon which to examine potential special considerations for DBD. A brief description of the DBD concept is provided in Appendix A: Deep Borehole Disposal.

Based on IAEA policy (IAEA, 2003) and model integrated safeguards approaches being developed by the IAEA (IAEA, 2010), the safeguards system for disposal facilities should be based on the following criteria.

1. Verifying design information throughout the life of the disposal facility (including design, construction and operation);
2. Maintaining CoK of nuclear material inventories in all facilities (encapsulation plant and geological repository, both above-ground areas and underground workings);
3. Verifying receipts and flows so that no nuclear material is removed by any declared or undeclared access routes; and
4. Detecting potential undeclared activities that could be associated with diversion.

The IAEA continues to consider the application of these criteria to MGR but has not considered their application to DBD concepts. Below, the ramifications of meeting these safeguards requirements when the disposal facility is a DBD facility are examined.

5.1. Verifying Design Information

Design Information Verification (DIV) is a crucial component of safeguards for a geological repository. Design verification involves review of a facility's design plans coupled with inspections. During design and construction of a repository, the IAEA's safeguards approach calls for DIV of surface buildings as well as the excavated subsurface areas in order to ensure the absence of undeclared features; e.g., hidden rooms or equipment. According to IAEA Policy Paper 15 (IAEA, 2003), the State should provide to the IAEA as early as possible the following information about its repository plans.

- Draft plans for the repository site
- Design information for nuclear-material containers, storage locations, and capacities
- Descriptions of intended exploratory underground works in the repository
- Design information about surface buildings at the repository site
- Information about existing local mines

The same information would be required for a State's DBD facility.

Before operations begin, activities are expected to be limited to site selection, facility design, and construction. Such activities fall within conventional DIV for nuclear facilities under IAEA safeguards and need not present greater difficulties than conducting DIV for a conventional MGR. In fact, the size and complexity of a conventional MGR makes effective DIV a major undertaking (Mongiello, Finch, & Baldwin, 2013), whereas, compared to a conventional MGR, the design of a deep borehole disposal facility might be much simpler (see Appendix A: Deep Borehole Disposal). MGRs are complex underground facilities envisioned to have multiple access points (ramps, shafts, etc.), all of which pose potential avenues for the undeclared removal of nuclear materials. By contrast, a borehole facility consists of one or more boreholes, each of which has only a single access point: the borehole itself. Thus, the (potentially) smaller scale and relative simplicity of deep-borehole design could make DIV easier than for a conventional MGR.

One acknowledged challenge for DIV at a mined repository (MGR) is the expectation that operations will involve concurrent excavation, emplacement, and backfilling. No such complications are envisioned for borehole facilities: drilling of a borehole to its design depth would be completed before emplacement of any waste canisters. Emplacement operations would then proceed to completion before backfilling operations could begin. Thus, for a single borehole, drilling, emplacement, and backfilling would be sequential and would not overlap, and this might help simplify DIV. However, if a DBD facility includes multiple boreholes, drilling, emplacement and backfilling of multiple, albeit separate, boreholes could be performed concurrently, potentially complicating DIV for the complete facility.

As noted in the section on Retrievability, the design of a borehole may depend in part on a State's requirement for retrievability. That is, a State that requires retrieval of waste canisters be considered in the design of a disposal facility would likely require borehole design (should they choose this disposal option) to enhance retrieval operations; e.g., through the use of steel liners or down-hole lubricants (Sapiie & Driscoll, 2009; Harrison, 2000). Another potential complication is the possible use of multiple "branched" boreholes stemming from a central borehole at the surface, as described elsewhere (Gibbs, 2010).

Verifying such design criteria might be an important part of DIV; however, the ability to verify the design of a deep borehole to depths approaching 5,000 meters could present a considerable challenge. The ability to verify design details of a borehole is more restricted than verifying underground designs for a conventional MGR due to a borehole's more limited access. Thus, if a borehole is designed to, for example, enhance retrievability (e.g., through sturdier borehole casing, specially designed canisters, and/or down-hole lubricants) such design factors would need to be verified (if possible) without direct underground access. Borehole DIV might be conducted by using downhole video cameras, calipers (sonic/acoustic or gamma), bonding logs, and the like – equipment that is currently used by the drilling industry. However, such methods are not yet used by the IAEA for safeguards-related DIV. Another potential methodology for remote monitoring of borehole drilling would be to use surface-based acoustic monitoring, much as envisioned for a conventional MGR (Mongiello, Finch,

& Baldwin, 2013), to track underground progress and verify borehole configuration[4] (multiple boreholes at a single DBD facility might reduce the effectiveness of this method). As for any new safeguards application of existing technologies, such applications for DIV applied to deep boreholes would need to be tested and certified for their efficacy.

5.1.1. Surface Facilities

As for a mined repository, a borehole disposal facility will require surface facilities for drilling and emplacement operations, receipt of and buffer storage for disposal canisters, administrative buildings, security barriers, etc. Verifying the design of surface facilities at a borehole facility should present no additional complications compared to DIV of surface facilities at a mined repository, and might, in fact, be somewhat simpler, depending on the scale of operations. However, some proposals for borehole disposal include drilling multiple boreholes at a single site; this could result in more complex demands on suitable DIV techniques, as noted above.

5.2. Maintaining CoK of Nuclear Material Inventories

CoK refers to maintaining, throughout a process or series of events, critical knowledge about items or materials of safeguards concern. Loss of CoK requires that the material or items be re-verified through visual inspection or measurement. As noted by (Fritzell, et al., 2008), the "safeguards system must create accurate information about spent fuel destined for disposal. Because the fuel cannot be re-verified after it is emplaced and the repository tunnels backfilled, information and any safeguards conclusions drawn from it must be clear, unambiguous, well documented, and accepted by all parties." The same is true— perhaps more so— for a DBD facility.

Once SNF is sealed inside a disposal canister, CoK must be maintained during transportation until final disposal, and well after. This must be accomplished through effective containment and surveillance. A deep borehole would constitute a situation that the IAEA refers to as "difficult to access", for which the IAEA requires that "dual containment and surveillance" measures be in place ("dual C/S"). That is, at least two *independent* methods must be used in order to assure CoK.[5] Until disposal canisters are emplaced underground, disposal canisters might be considered to constitute the primary containment for SNF they contain. Verifying a canister's integrity, e.g., by inspecting a seal, could provide at least one independent C/S measure; however, whether disposal canisters can be effectively sealed in a way that assures detection of tampering is a major challenge that remains to be solved. Disposal canisters will be transported from the encapsulation plant to the disposal facility (either DBD or MGR) in purpose-built transport casks (aka "overpacks") that will be sealed with tamper-indicating seals and possibly tracked during transport. Thus transport casks may constitute secondary containment. The ability to emplace a canister into a borehole

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[4] "Configuration" means overall geometry, for example, rather than detailed design features, such as casing materials or other internal features.

[5] Note that the two C/S methods used for "dual C/S" are not simply redundant measures, where only one of the measures verifies positively. Rather, both measures must verify positively to conclude that CoK has been maintained; if either should verify negatively, CoK has been lost (Baldwin, Haddal, & Finch, 2016).

directly from its transport cask is a potential advantage of DBD for maintaining CoK compared with a conventional MGR, as discussed in more detail in the section on Verifying Receipts and Flows.

Once emplaced underground, the host rocks at depth constitute primary containment, and assurance that there is no access following closure provides adequate assurance that no canisters have been removed. Dual C/S may require that two independent measures be used for surveillance; e.g., satellite or aerial imagery plus seismic/acoustic monitoring. Long-term monitoring and surveillance after closure is discussed in the section on Long-Term Safeguards Post-Closure.

As for a conventional MGR, the need to maintain long-term CoK of nuclear-material inventories may be questionable (Baldwin, Haddal, & Finch, 2016). Once the canister is successfully emplaced in a borehole for permanent disposal and the borehole sealed, the nuclear material inventory will be largely irrelevant, as recovery of properly disposed canisters for re-verification is not realistic.[6]

5.3. Verifying Receipts and Flows

There are three overarching components to consider for material receipt and flows for a DBD system: the encapsulation plant, transportation from the encapsulation plant to the disposal facility, and the disposal facility. These are discussed in order.

Verifying receipts and flows of nuclear material for an encapsulation plant are discussed in more detail in a previous section (Encapsulation Plant); however, unless SNF assemblies are dismantled before encapsulation (see Appendix A: Deep Borehole Disposal), safeguards measures applied to verifying receipts and flows of nuclear material for an encapsulation plant that produces disposal canisters for emplacement in a DBD facility will be very similar to those in place at a more conventional encapsulation plant (Mongiello, Finch, & Baldwin, 2013; IAEA, 2010).

As described in the section on Transportation, safeguards assurance for canister transport entails two basic elements:

1. Every canister with verified nuclear material is delivered to the disposal facility, and
2. The integrity of the canisters is maintained at all times.

These requirements are the same as for a conventional MGR.

Once disposal canisters have arrived at the disposal facility (whether MGR or DBD), safeguards assurance entails three basic elements (Baldwin, Haddal, & Finch, 2016):

1. All canisters are delivered to disposal locations underground,
2. The canisters are not opened underground, and
3. No canisters are removed from the repository.

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[6] The same is true for a conventional MGR (Mongiello, Finch and Baldwin 2013).

All three elements are necessary, but in the case of a DBD facility, there is no possibility to open canisters underground (certainly not within a borehole). Ensuring the first and third criteria requires adequate C/S measures. Monitoring for undeclared retrieval of canisters during operations could be achieved through the use of directional radiation monitors at the top of a borehole, probably in combination with other surveillance measures such as optical or infrared cameras, for example.[7] The thinner-walled canisters envisioned for DBD could ease radiation detection. The smaller DBD canisters might also make undeclared movement or "swapping" more difficult to detect compared with the much-larger and more massive canisters designed for a conventional MGR.

One potential safeguards advantage of DBD compared to a conventional MGR is the manner in which emplacement is likely to be accomplished. Unlike a conventional MGR, emplacing a canister into a borehole can be performed in a single operation; whereas, emplacing a disposal canister into a conventional MGR is likely to require the canister be removed from the transport cask in one operation, followed by emplacement of the canister in an area separate from where safeguards seals are removed and the transport cask opened. By contrast, emplacing a disposal canister for DBD can proceed by emplacing the canister into the borehole directly from the cask in a single operation (Sassani & Hardin, 2015). That is, a sealed transport cask is placed directly over the borehole, the tamper-indicating seal can then be inspected, verified, and removed while the canister sits directly over the borehole. Once seals are removed from the transport cask,[8] it is opened and the disposal canister is lowered directly into the borehole, all in a single operation, which also can be conducted under surveillance. Only after the canister has been lowered into the borehole [either completely for single-canister emplacement, or part way if multiple canisters are to be emplaced simultaneously in a "string" (Sassani & Hardin, 2015)] is the empty cask removed from above the borehole. The empty transport cask could be verified as being empty through inspection or surveillance. Thus, emplacement of a disposal canister in a single operation, without the need to transfer a canister for emplacement after its removal from a transport cask, may simplify the ability to assure canisters are emplaced as declared at a DBD facility. This could be an important advantage for DBD in maintaining CoK on SNF disposal canisters through emplacement.

5.4. Detecting Potential Undeclared Activities

Like a conventional MGR, a DBD facility can be described as having three phases of operation: pre-operational phase (site selection, design, construction), operational phase (receipt and disposal of waste canisters), and post-operational phase (closing and sealing the borehole and decommissioning surface facilities).

5.4.1. Pre-Operational Phase

Before operations begin, activities are expected to be limited to site selection, facility design, and construction; that is, no SNF will be received or located at the DBD site

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[7] Retrieval of canisters after emplacement in a borehole is discussed in more detail in the section on Retrievability.

[8] Design of a transport cask consistent with this operation would likely require a minimum of two seals, as the transport cask would require two openings, one at either end of the cask (Sassani and Hardin 2015).

during this phase. Such activities fall within conventional DIV for nuclear facilities under IAEA safeguards and so should not present greater difficulties than DIV for a conventional MGR, except as discussed in the section on Verifying Design Information. No monitoring of receipts and flows of nuclear material will be required during this phase, except to the extent that any undeclared movements of nuclear material can be detected; e.g., through inspection or surveillance.

5.4.2. Operational Phase

During operations, a disposal facility will receive disposal canisters and emplace them underground. A conventional MGR is envisioned to include concurrent construction, emplacement, and backfilling. This can make DIV for a conventional MGR extremely complex, as discussed in the section on Verifying Design Information. Such complications are not envisioned for a DBD facility. A deep borehole must be drilled to completion before emplacement begins, and emplacement must be completed before backfilling begins. One potential complication might be if a DBD facility is drilling multiple boreholes, which might complicate DIV to some degree, especially if acoustic monitoring is being used to track drilling progress.

The receipt and emplacement of waste canisters during operations was discussed in the section on Verifying Receipts and Flows; however, we emphasize the importance of verifying that waste canisters are emplaced as declared. While this is also important for a conventional MGR, the visual inspection of underground workings at a conventional MGR is possible and even expected during both pre-operational and operational phases. Options for verifying that canisters have been emplaced as declared are more limited in the case of DBD, and no direct inspection is possible. On the other hand, as discussed in the section on Verifying Receipts and Flows, the potential to maintain CoK on disposal canisters up to emplacement is a borehole may be a safeguards advantage of DBD.

If an empty or “dummy” canister were to be successfully emplaced instead of a full one that has been diverted, there would be no possibility of discovering this after emplacement (except to discover the diverted canister). If an empty, “cold” canister was emplaced, it would pass a directional radiation monitor (used to detect undeclared removal of canisters) without producing a signal. If this were to happen, the emplacement operation would need to be halted and reversed so the empty canister could be recovered. Some designs envision emplacing strings of multiple canisters in a single operation (see Appendix A: Deep Borehole Disposal), and the potential effect of this methodology on effectively assuring the emplacement of all canisters as declared may need special consideration and evaluation. Such potential complications further emphasize the very strong need to rely on effective CoK for DBD facilities, as strong as or stronger than for a conventional MGR.

Many other safeguards measures envisioned for a conventional MGR would also apply to the operational phase of a DBD facility. These include site inspections and environmental monitoring (e.g., for undeclared retrieval or diversion of canisters and other undeclared activities). However, there is little or no possibility for canisters to be opened within a borehole. Unlike a conventional MGR, with its complex underground workings, underground activities are unlikely at a dedicated DBD facility; that is, on-site clandestine facilities would be separate from boreholes and (perhaps) more readily detected during routine inspections and DIV.

5.4.3. *Retrievability*

One critical issue for maintaining effective safeguards on nuclear materials disposed in a deep borehole is whether (and perhaps how readily) nuclear material emplaced in the borehole can be retrieved. Some countries require that nuclear-waste disposal be demonstrably retrievable to varying extents (Haverkate, 2005).

A country that requires its waste disposal concept allow for retrieval of wastes will stipulate that retrieving canisters be a design criterion, whereas countries without such a requirement may not. In the case of DBD, requiring retrievability of waste canisters necessitates that disposal canisters be designed to be readily accessed and recovered from the borehole, as well as the potential for designing canisters to have longer lifetimes underground compared to disposal concepts for which no retrieval is envisioned (Harrison, 2000). Compared with MGR, the disposal of spent fuel or other nuclear materials in deep boreholes three to five km below the surface may make retrieval more difficult, although certainly not impossible (Nirex, 2004; Sapiie & Driscoll, 2009). Indeed, many studies of borehole disposal suggest that retrieving waste canisters from deep boreholes is possible with current technologies, regardless of design (National Academy of Sciences, 1994; Swahn, 1996; Harrison, 2000; Sapiie & Driscoll, 2009). However, the means to do so could seriously damage emplaced canisters, especially those not specifically designed for retrieval. Furthermore, technologies for retrieving materials from deep boreholes, already a standard practice in the oil and gas industry, will continue to evolve and improve, increasing the ease of retrieval in the future. The ability to retrieve waste packages from (shallow) boreholes was demonstrated three decades ago (Patrick, 1986), and retrieving waste canisters from very deep boreholes will be further developed as part of a proposed pilot project in the US (MacKinnon, 2015; Arnold, et al., 2012).

In an early report by the NAS (National Academy of Sciences, 1994), it was concluded that the simplest approach for retrieving waste from a closed and sealed borehole would involve re-drilling the borehole(s), an operation considered to be relatively easy for sections filled with bentonite. In this way, a string of canisters could be reached and retrieved, assuming those canisters remained intact. The only major differences from conventional drilling would be the requirement to follow the pilot hole and understand details about access to canisters. If the operation were to be conducted at a time when the canisters had ruptured or corroded, a more complex approach with greater safety and health precautions would be required, but the NAS considered that the waste would remain retrievable indefinitely at “somewhat greater cost” than during borehole operations (National Academy of Sciences, 1994). The NAS also concluded that drilling operations to retrieve nuclear material would be highly visible, so that a State would have difficulty retrieving nuclear material without detection. To make retrieval more difficult, the NAS considered that boreholes could be made harder to re-drill by embedding extremely hard material in the mud and concrete with which the hole is backfilled.[9] Conversely, retrieval can be made easier, if desired, through a variety of methods, including steel liners and down-hole lubricants (Sapiie & Driscoll, 2009). Two potentially important considerations for safeguards implementation will be borehole design and national policy on retrieval. The latter is readily confirmed, whereas the former may present considerable challenges for design verification.

Nearly all considerations of borehole disposal acknowledge the possibility that, during emplacement operations, a canister (or string of canisters) could become lodged within a borehole above the intended disposal depth. In such a case, it may be decided to abandon the borehole with the (improperly) emplaced canister(s) or to retrieve the lodged canisters if the hole cannot be safely abandoned [see, for example, (Arnold, et al., 2012)].

The return to the surface of any disposal canister(s) containing nuclear material under safeguards requires that appropriate safeguards protocols be in place, and that the nuclear material in the recovered canister(s) be appropriately accounted for. The capability of a State to recover canisters from depth further necessitates that effective measures remain in place to detect undeclared recovery of waste canisters after they have been emplaced underground. In the case of a conventional MGR, this is generally envisioned to include portal radiation monitors and other C/S measures, such as surveillance cameras, to help ensure that no canisters containing nuclear material are returned to the surface undeclared. A similar approach is anticipated for a DBD facility.

Unlike a borehole, a mined repository will have multiple access points, including ramps and shafts, potentially making the effective use of portal monitors and other C/S measures more complex for a conventional MGR than for a DBD facility (IAEA, 1998; IAEA, 2010). In the case of deep boreholes, access to canisters that have been lowered into the borehole will be through the borehole itself, as no other access is envisioned. This single point of entry and exit should simplify the implementation of C/S measures used to detect undeclared retrieval of emplaced canisters (e.g., directional radiation monitors).

Once a borehole is at its design capacity and is backfilled, sealed, and closed, the retrieval of emplaced canisters becomes considerably more difficult (Arnold B. W., et al., 2013, pp. A-14). Indeed, retrievability may be “moderately difficult for [an] initial period (up to about 100 years), [becoming] more difficult with time, [and] might require over-boring technology [that is] beyond current state-of-the-art” (Nirex, 2004). Effectively monitoring a closed borehole and its surroundings in order to detect undeclared activities, including potential recovery of items or material from a closed and sealed borehole, may be required for many years after post-closure, depending on a State’s safeguards agreement. How to accomplish that is an active area of R&D for conventional MGRs as well. The potential retrieval of waste canisters from a deep borehole makes the application of IAEA safeguards a long-term requirement, at least

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[9] Verifying that post-closure sealing of a disposal facility, whether DBD or MGR, has not been addressed by the IAEA, and the means to effectively do so after such sealing is complete may not exist.

during the facility's entire operational phase and possibly well after closure (IAEA, 2003).

5.4.4. Long-Term Safeguards Post-Closure

Very long-term monitoring of a repository is an active area of R&D in support of the IAEA's safeguards programs, and a model safeguards approach to conventional MGRs has been proposed (IAEA, 2010) with further discussion provided in a recent Sandia report (Mongiello, Finch, & Baldwin, 2013). As for a closed and sealed conventional MGR, the site of a closed and sealed DBD facility may require long-term monitoring for potential undeclared activities. This could be accomplished by using the same means by which a conventional MGR would be monitored; that is, by periodic site inspections, seismic/acoustic monitoring, and satellite or other aerial imagery.

Several methods proposed for long-term monitoring of mined geological repositories should apply equally well to monitoring deep borehole after closure. For example, passive seismic monitoring can be used to detect undeclared activities (e.g., re-drilling) which might indicate attempts to illegitimately recover spent fuel emplaced underground. Remote sensing with satellite- or aerial-imaging techniques can reveal changes that may indicate undeclared or illicit activities, including clandestine re-drilling of an existing deep borehole. Some authors have suggested that long-term active monitoring of a DBD facility would be less important than for a conventional MGR (Bates, Driscol, Lester, & Arnold, 2014). Most certainly, several methods that might conceivably be used to recover nuclear materials from a conventional MGR could be eliminated as inapplicable to recovering materials from a sealed deep borehole (e.g., conventional mining or tunnel-boring machines).

Once fuel is emplaced underground and a borehole is sealed, there is no monitoring method under current consideration that is able to verify the declared inventory of, or to detect nuclear material missing from, a deep borehole.[10] It therefore seems worth exploring novel methods that might be applied to long-term monitoring of deep boreholes after closure. One example is the potential use of Interferometric Synthetic Aperture Radar (InSAR) to detect surface deformation caused by thermal expansion of host rock due to the disposal of heat-producing waste, such as SNF (Travis, McTaggart, Gibb, & Burley, 2008).[11] Such novel monitoring methods might provide added assurance about the continued presence of buried waste, and detect its removal, should more conventional efforts fail to detect attempts at recovery.

A potential complication for monitoring undeclared attempts to access a DBD facility compared with the same task for a conventional MGR concerns the surface area over which safeguards monitoring might need to be applied. Of course, any MGR could be re-mined from the surface above the underground facility; however, most MGRs might also be accessed through the use of tunnel-boring machines and other conventional mining methods that might seek ingress from a considerable distance away from the MGR (Peterson, 1996). Given the depth of most planned MGRs, the

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[10] The same is true for a conventional MGR after closure.

[11] Remote sensing of surface deformation can be accomplished using InSAR measurements by satellite with a resolution of one millimeter (1 mm) vertical displacement under favorable conditions (Jasani 2009).

area to be monitored might be limited to a radius of one to two kilometers (Peterson, 1996), whereas the distance from a closed DBD facility from which a drilling rig could be sited is uncertain (Figure 1). The most readily achievable recovery would be to re-drill the existing borehole (the location of which would be known); however, current drilling technologies can allow for access from a considerable distance away by using directional drilling techniques. Such capabilities were demonstrated when a relief well was drilled to stanch oil flow during the Deepwater Horizon oil spill in 2010 (New York Times, 2010).

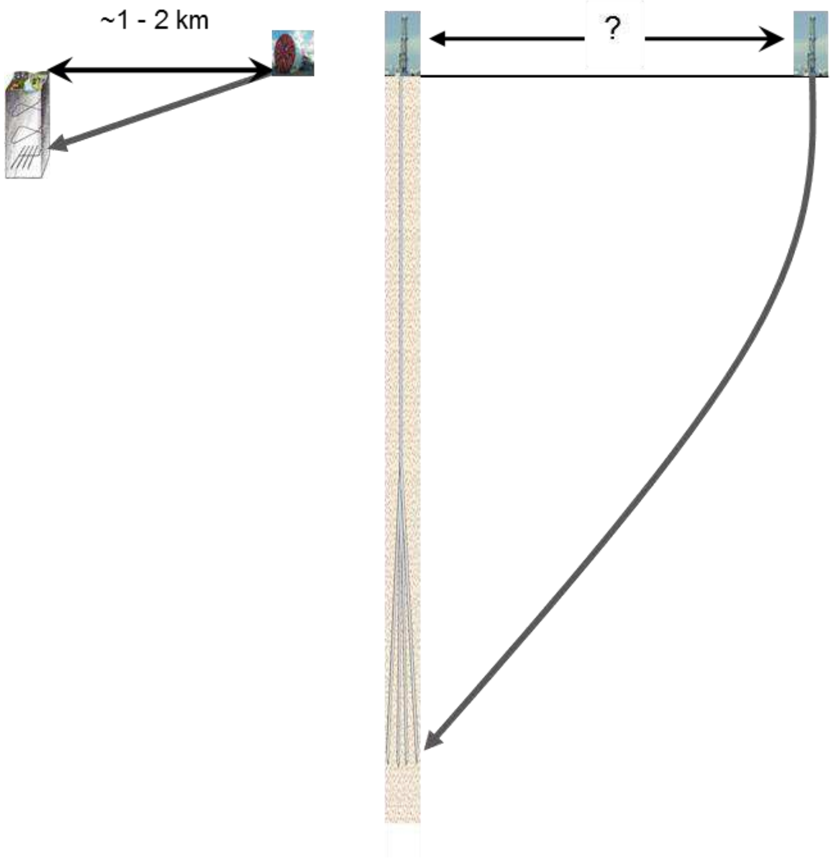

Figure 1. Comparison of access depths and associated areal monitoring radii for MGR vs. DBD facilities.

6. COMPARING SAFEGUARDS FOR DBD AND MGR

Safeguards concern	Mined Geological Repository (MGR)	Deep Borehole Disposal (DBD)
Design Information Verification	Extensive, complex underground facility subject to change during operations. Access to underground permits inspections, mapping, ground-penetrating radar Remote monitoring possible with acoustic monitoring. Simultaneous construction, emplacement & backfill add complexity.	Small-scale, straightforward design. No direct underground access. Conventional borehole measuring & logging devices may be adaptable to use for DIV. Surface-based acoustic monitoring might be used to follow drilling progress and basic configuration. Multiple boreholes at a single facility might add complexity to DIV.
Canister emplacement as declared and without undeclared removal	Portal monitoring of multiple access points with surveillance cameras and radiation monitors (directional). Verify CoK on transport casks, either at the surface with transfer of canisters underground (monitored at ramp entrance), or seals on casks are verified underground, with empty casks returned to the surface and canisters transferred to final emplacement positions. May be possible to verify emplacement underground through inspections before repository closure.	Potentially stronger reliance on CoK than for MGR. Portal monitoring of single access point with surveillance cameras and radiation directional monitors. Verify canister emplacement at surface (crucial), but this may be easier than for MGR. No possibility to directly inspect emplacement underground, but tools for down-hole monitoring and/or inspection may be adaptable for safeguards use.

Safeguards concern	Mined Geological Repository (MGR)	Deep Borehole Disposal (DBD)
Retrievability	May be straightforward before closure (depending on design and operations), but much more difficult after closure. Post-closure recovery of canisters by conventional mining methods, TBMs, etc. A canister recovered by re-mining may not retain its identity (or seal) for safeguards purposes, with concomitant loss of CoK.	Drilling industry has ample experience with down-hole recovery. Design considerations might facilitate retrieval operations during operations. Probably more difficult than retrieval from MGR after closure, depending in part on final sealing design. Post-closure access to waste requires re-drilling or remote directional drilling. A canister recovered by re-drilling may not retain its identity (or seal) for safeguards purposes, with concomitant loss of CoK.
Post-closure monitoring	Periodic site inspections, seismic/acoustic monitoring, satellite and/or aerial imagery Monitored area probably limited to *ca*. 1 -2 km radius.	Similar to MGR. Less need to detect certain technologies (e.g., TBM). Greater difficulty with post-closure waste recovery may reduce need for long-term post-closure monitoring. Potentially greater area to monitor.

7. CONCLUSIONS AND RECOMMENDATIONS

In comparing potential safeguards approaches for SNF disposal in a conventional MGR with possible safeguards approaches for a DBD facility, we find that many aspects of safeguards will likely be similar. A few differences may prove considerably more challenging, while others might simplify or even eliminate certain safeguards requirements.

In most regards, the safeguards approach for an encapsulation plant used for encapsulating SNF for a DBD facility should not differ from the approach used for a plant that encapsulates SNF for disposal in a conventional MGR. One potential difference concerns whether a DBD design requires SNF assemblies be dismantled and individual fuel pins consolidated in disposal canisters. Such a design could significantly challenge inventory accountancy and CoK. Should such an approach be taken, a suitable safeguards approach for maintaining CoK on separate fuel pins will need to be developed. We make no suggestions in this report beyond the need to implement adequate surveillance measures.

No substantive difference is envisioned in applying safeguards during transport of SNF canisters to a DBD facility compared with safeguards measures envisioned for transport of SNF canisters to a conventional MGR, as both types of disposal options require transport casks (“overpacks”) to be sealed and probably tracked during shipment.

We find more, and more substantive, differences in potential safeguards approaches for the two kinds of disposal facility: DBD vs. a conventional MGR. Four main safeguards criteria are most affected:

1. Verifying design information
2. Maintaining CoK of nuclear material
3. Verifying receipts and flows
4. Detecting undeclared activities.

7.1. Design Information Verification (DIV)

Conducting DIV for a DBD facility should present few additional complications compared to DIV for a conventional MGR, and some might, in fact, be somewhat simpler, depending on the scale of operations. However, some proposals for borehole disposal include drilling multiple boreholes at a single site, which could lead to more complex demands on DIV. Verifying that boreholes are drilled and otherwise constructed as designed would likely be done in a manner quite different from that envisioned for DIV for the underground workings of a conventional MGR, where inspector access to underground workings will be available throughout the operational phase; that is, until final closure. By contrast no such access is possible for inspecting a borehole below ground. Nevertheless, the extent and maturity of the drilling industry means that several commercial-off-the-shelf (COTS) tools are available to inspect boreholes and are already used by the industry on a regular basis. Such tools may well prove invaluable for DIV of a DBD facility, provided they can be adapted and certified for safeguards use by the IAEA. Some tools potentially applicable for DIV are discussed in a separate appendix (Appendix B: Down-Hole Inspection Equipment), and include down-hole video cameras, calipers (sonic/acoustic or gamma), etc. Another potential methodology for remote monitoring of borehole drilling would be to use surface-based acoustic monitoring, much as envisioned for a conventional MGR (Mongiello, Finch, & Baldwin, 2013), to track underground progress and to verify borehole configuration. The relative 'quiet' of borehole drilling compared with conventional mining techniques used in constructing a MGR may require adaptation of this method to borehole construction.

7.2. Maintaining CoK through Effective C/S Measures

Once SNF is emplaced underground at a conventional MGR and underground access has been backfilled and sealed, all safeguards conclusions "must be clear, unambiguous, well documented, and accepted by all parties" (Fritzell, et al., 2008). The same is true—perhaps more so—for a DBD facility.

As noted above, maintaining CoK on SNF during encapsulation and transportation should not present major differences from the same activities for a conventional MGR, except as noted above. Disposal canisters will be transported from the encapsulation plant to the disposal facility (either DBD or MGR) in purpose-built transport casks that will be sealed with tamper-indicating seals and possibly tracked during transport. However, in the case of a DBD facility, the ability to emplace a canister into a borehole directly from its transport cask in a single operation is a potential advantage of DBD for maintaining CoK compared with a conventional MGR.

7.3. Verifying Receipts and Flows of SNF

For the most part, there is little difference between disposal concepts when it comes to verifying receipts and flows of SNF. As noted, disposal canisters with SNF will arrive at a DBD facility in much the same manner as conventional disposal canisters will arrive at a conventional MGR. They will be in transport casks with tamper-indicating seals, and these will be inspected and verified upon receipt, regardless of facility type.

One the other hand, the emplacement method for DBD differs from that of a conventional MGR. The ability to emplace a canister into a borehole directly from its transport cask is a potential advantage of DBD for maintaining CoK compared with a conventional MGR. Because borehole emplacement can be accomplished during one continuous operation, the tamper-indicating seal on the transport cask can be inspected, verified, and removed while the canister sits directly over borehole. Once the seal(s) are removed from the transport cask, it is opened and the disposal canister is emplaced directly into the borehole, all in one continuous operation that can be conducted under surveillance. The empty transport cask can then be verified as empty by direct inspection or surveillance. In this way, the DBD concept could simplify the ability to verify that canisters are emplaced as declared, and could be an important advantage for DBD over conventional MGR in maintaining CoK on SNF disposal canisters through emplacement.

7.4. Detecting Undeclared Activities

During the operational phase of a DBD facility, most safeguards measures envisioned for a conventional MGR would apply to a DBD facility. These include site inspections and environmental monitoring (e.g., for undeclared retrieval or diversion of canisters, and undeclared activities). One significant difference is the fact that canisters cannot be opened and SNF removed within a borehole. Unlike a conventional MGR with its complex underground workings, underground activities are unlikely at a dedicated DBD facility; that is, on-site clandestine facilities would be separate from the boreholes and (perhaps) more readily detected during routine inspections and DIV.

If an empty or "dummy" canister were to be successfully substituted for a full one that has been diverted, there might be little or no possibility of discovering this after the dummy has been emplaced down hole (except to find the diverted canister). Avoiding such a scenario is best assured through effectively maintaining CoK through C/S; the potential benefit of DBD emplacement to maintain CoK has already been discussed.

7.5. Retrievability

Differences in design, complexity and other aspects between a DBD facility and a conventional MGR lead to some unique considerations about safeguards approaches for DBD. Effectively ensuring that no canisters containing SNF are returned to the surface undeclared might be accomplished by using portal radiation monitors and other C/S measures, such as surveillance cameras, at all access points. Unlike a borehole, a mined repository will have multiple access points, including ramps and shafts, potentially making the effective use of portal monitors and other C/S measures more complex for a conventional MGR than for a DBD facility. By contrast, the single point of entry and exit for a DBD facility should simplify the implementation of C/S measures used to detect undeclared recovery of emplaced canisters (e.g., directional radiation monitors).

Recovery of buried SNF after borehole closure will be difficult; however, it might be made more difficult to re-drill the borehole by embedding extremely hard materials in the mud and/or concrete with which the hole is backfilled. Conversely, retrieval might be eased through a variety of methods, including steel liners and down-hole lubricants. Verifying such design features after the borehole backfilled and sealed would be an unprecedented demand on DIV, and post-closure access to a borehole would be monitored by methods already under consideration for a conventional MGR (addressed in the next section). On the other hand, confirming the design of a borehole before closure might be accomplished with the help of existing technologies adapted for safeguards use (see above and Appendix B: Down-Hole Inspection Equipment).

7.6. Long-Term Monitoring

A closed and sealed DBD facility is likely to be monitored over the long term for potential undeclared activities by using the same methods envisioned for long-term monitoring of a conventional MGR; that is, by periodic site inspections, seismic/acoustic monitoring, and satellite or other aerial imagery. Largely because of its depth, several methods that might be used to recover SNF from a conventional

MGR after closure cannot be used to recover SNF from a sealed deep borehole (e.g., conventional mining or tunnel-boring machines), so that the need to develop monitoring techniques to detect such activities is obviated. And while drilling might not be as “noisy” as many conventional mining techniques, potentially making acoustic detection more difficult, the fact that such an operation would require equipment at the surface might make visual detection easier.

One potential added difficulty of effectively monitoring for undeclared access to SNF disposed in a deep borehole is the surface area around the borehole that might need to be monitored. Because of advances in directional drilling, the area to be monitored might be considerably larger than for a conventional MGR. Whether a deep borehole will require safeguards monitoring for an indeterminate period far into the future may depend on a better understanding about the risks of SNF being recovered from such depths after such a long time underground.

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APPENDIX A: DEEP BOREHOLE DISPOSAL

Although deep borehole disposal (DBD) has been discussed as a possible waste-disposal option since the late 1950s (National Research Council, 1957), the disposal of high-level radioactive waste and spent nuclear fuel (SNF) has focused almost exclusively on mined geological repositories (MGR), with the US, Sweden, and Finland leading those efforts for most of the last quarter of the 20th century and into the early 21st century. Nevertheless, periodic evaluations of the DBD concept have been conducted by several countries (Al Bloushi, Beeley, Kim, & Lee, 2015; Bates, Driscol, Lester, & Arnold, 2014; DOE, 1996; DOE, 2014; Åhäll, 2006; Swahn, 1996; Nirex, 2004).

The DBD concept consists of drilling a borehole into crystalline basement rock (typically granitic rock) to a depth of about 5,000 m, emplacing waste canisters containing SNF or vitrified radioactive waste from reprocessing in the lower 2,000 m of the borehole, and sealing the upper 3,000 m of the borehole. The concept is illustrated in Figure 2, showing the borehole disposal depth relative to the typical depth for mined repositories of several hundred meters. Because a DBD system is six to ten times deeper than a typical mined repository, DBD is seen to provide considerably greater isolation from the surface and near-surface environments. Such increased isolation is a potential safety benefit, but it could also impact nuclear security and international safeguards. Despite a great deal of recent enthusiasm for the concept, however, DBD still faces considerable engineering challenges (NWTRB, 2013; Beswick, Gibb, & Travis, 2014). Technical requirements for DBD are described in more detail elsewhere (Arnold B. W., et al., 2011) and summarized in the following section, Technical Requirements of the Reference Design

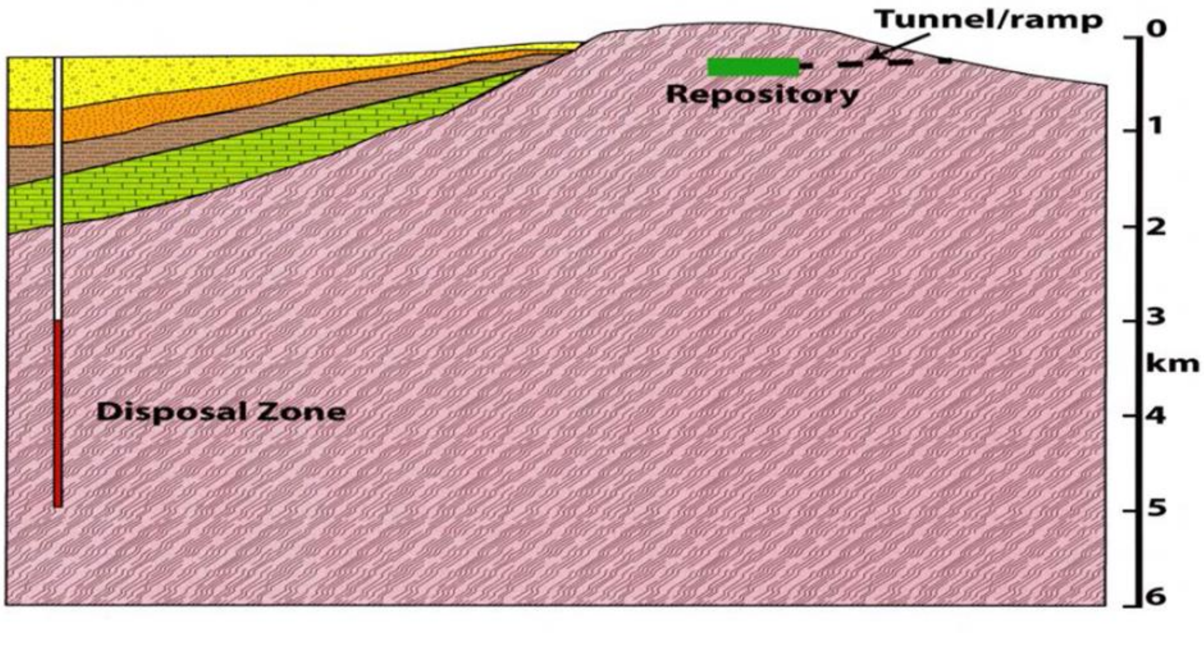

Figure 2. Schematic diagram of the deep borehole disposal concept (NWTRB, 2013).

A nominal reference design for a DBD system has been described (Arnold B. W., et al., 2011). Each borehole would be drilled and cased in stages, with the borehole's diameter decreasing from about 1.2 meters at the surface to less than one-half meter in the disposal interval (Figure 3). In order to help prevent potential crushing of underlying canisters during the operational period, bridge plugs would be used in the borehole. Canisters would be surrounded by bentonite slurry and the upper 3,000 m of the borehole would be sealed by a combination of compacted bentonite packs and concrete plug (Figure 4).

Emplacing intact spent fuel assemblages, without pre-consolidation, is one of the simplest approaches to borehole disposal; however, consolidating fuel pins is also seen as a way to maximize the mass of SNF that could be disposed in each borehole (Arnold B. W., et al., 2011).

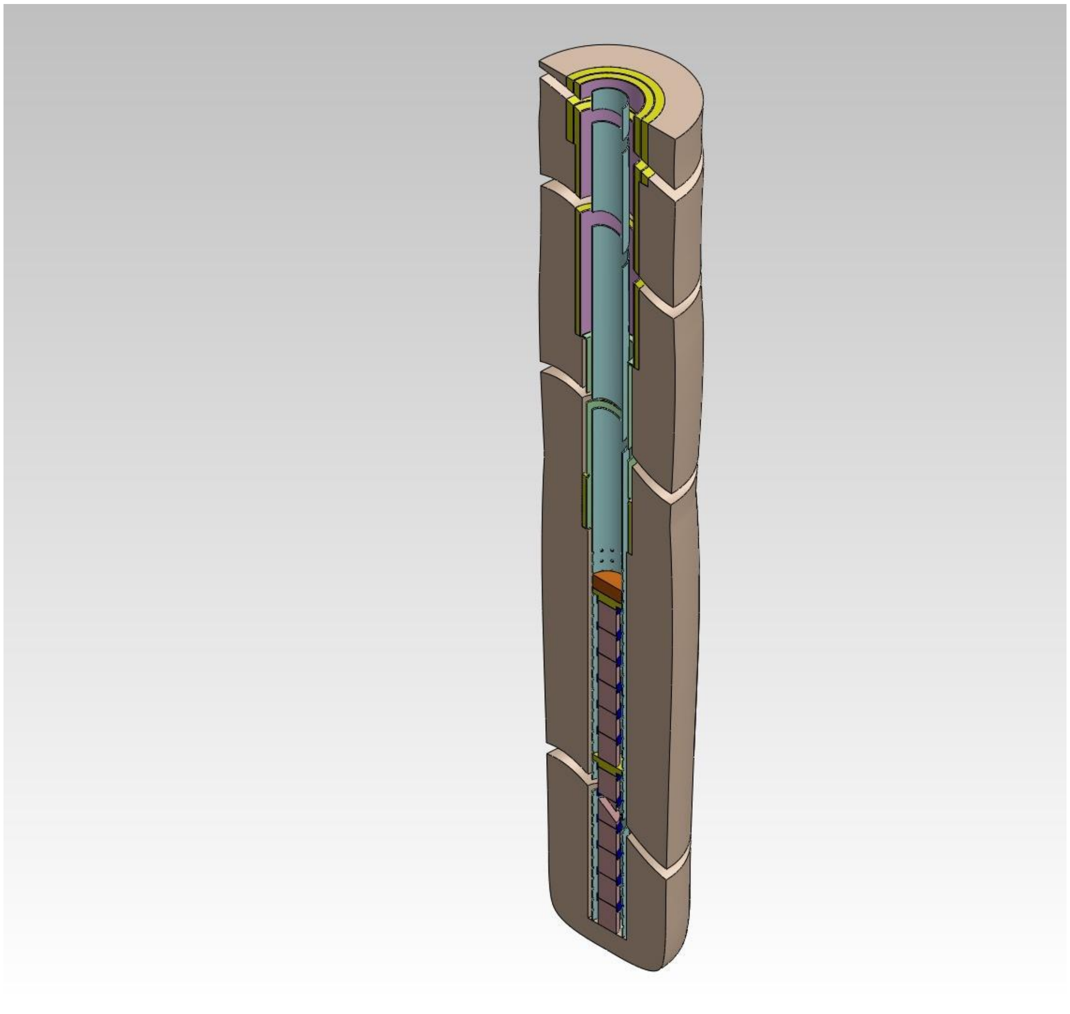

Figure 3. Schematic depiction of a completed borehole. Not to scale; borehole seals not shown. Configuration shown is after waste has been emplaced and the overlying cement plug has been set, but before the casing has been cut and removed (Arnold B. W., et al., 2011).

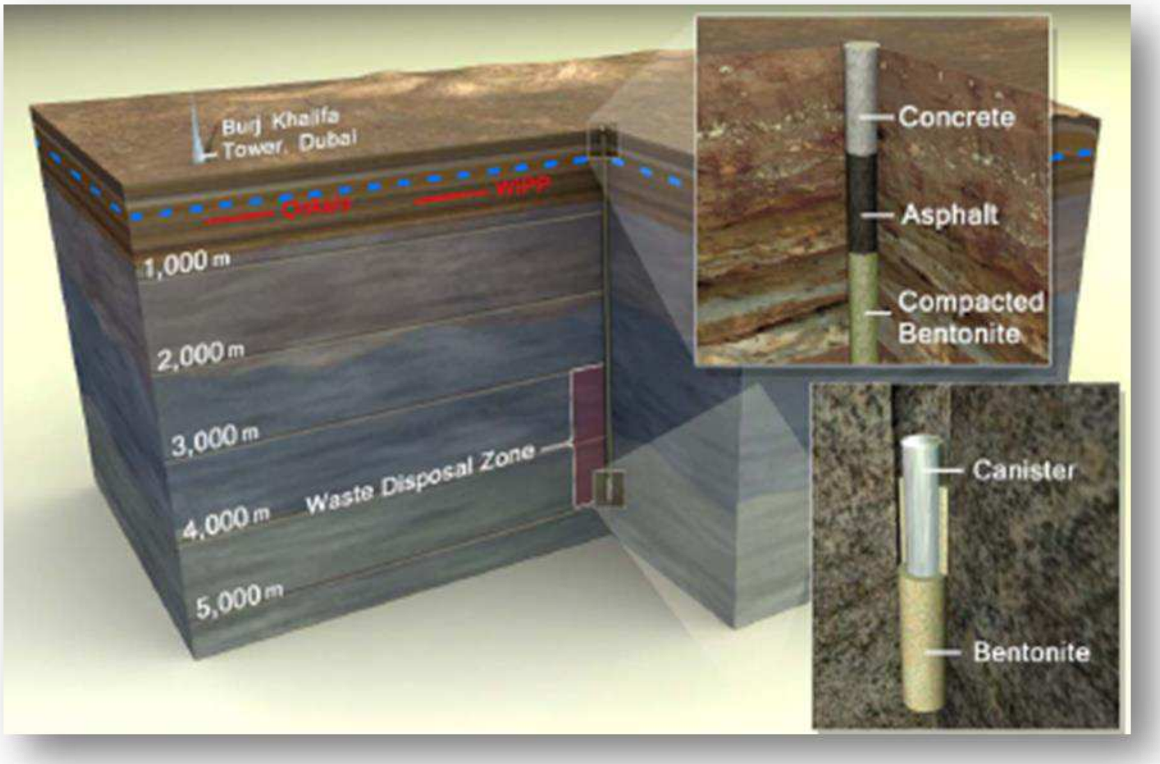

Figure 4. Deep borehole reference design concept. Figure 1 from (Arnold B. W., et al., 2011).

If spent-fuel assemblies are disposed intact, a disposal canister approximately 5m tall with an inner diameter of 32 cm could hold one pressurized water reactor (PWR) assembly (Brady, et al., 2009). Alternatively, four intact boiling water reactor (BWR) fuel assemblies could be placed inside a 4.8m long titanium cylinder 0.5m in diameter (Birgersson, Skagius, Wiborgh, & Widén, 1992). In this concept, voids in waste packages are filled with concrete. These waste packages are emplaced in the bottom 2,000m of a 4,000m deep, 0.8m diameter borehole fitted with 0.6m diameter titanium casing. The annulus between the packages and casing is filled with a high-density deployment mud and the packages separated vertically by a 1 m long cylinder of compacted bentonite, which is a swelling clay. Above the deployment zone, the hole is sealed with bentonite, and the top 500m is sealed with asphalt topped by a concrete plug.[12]

In order to maximize the mass of fuel to be disposed, an alternative disposal method is to disassemble the fuel assemblies and load individual fuel pins into each disposal canister. Such a design is depicted in Figure 5. As noted by (Arnold B. W., et al., 2011), this procedure entails greater cost and effort in the loading of the waste canisters; however, it allows for a smaller diameter waste canister, a smaller diameter borehole, and greater operational assurance for the construction of the borehole to the required depth. The higher density of used fuel in the waste

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[12] Asphalt is no longer considered in many current DBD design proposals because of its potential to release dissolved organic acids that might enhance radionuclide transport (Patrick V. Brady, personal communication).

canisters also results in fewer total waste canisters, fewer boreholes, and lower transportation, drilling and operational costs. Some disposal scenarios envision relatively high temperatures, as well as emplacement methods that would encase disposal canisters in a solidified matrix [e.g., (Gibb, Travis, & Hesketh, 2012)]. Such scenarios would impact post-emplacement canister retrieval, probably making it considerably more difficult. Fuel consolidation technology and costs have been analyzed in previous studies (Gibbs, 2010). Details about canister loading for the Sandia reference design are summarized in the section on DBD Design and Cost Considerations.

Whether a State chooses to dispose of intact fuel assemblies or to consolidate individual fuel pins before disposal will depend on a number of factors; however, the method of consolidating fuel pins could greatly complicate nuclear material accountancy for safeguards. We emphasize here that the disposal system in the Sandia Laboratories DBH reference design is based on the disassembly of used nuclear fuel assemblies and loading of individual fuel pins into waste canisters, as shown in Figure 5.

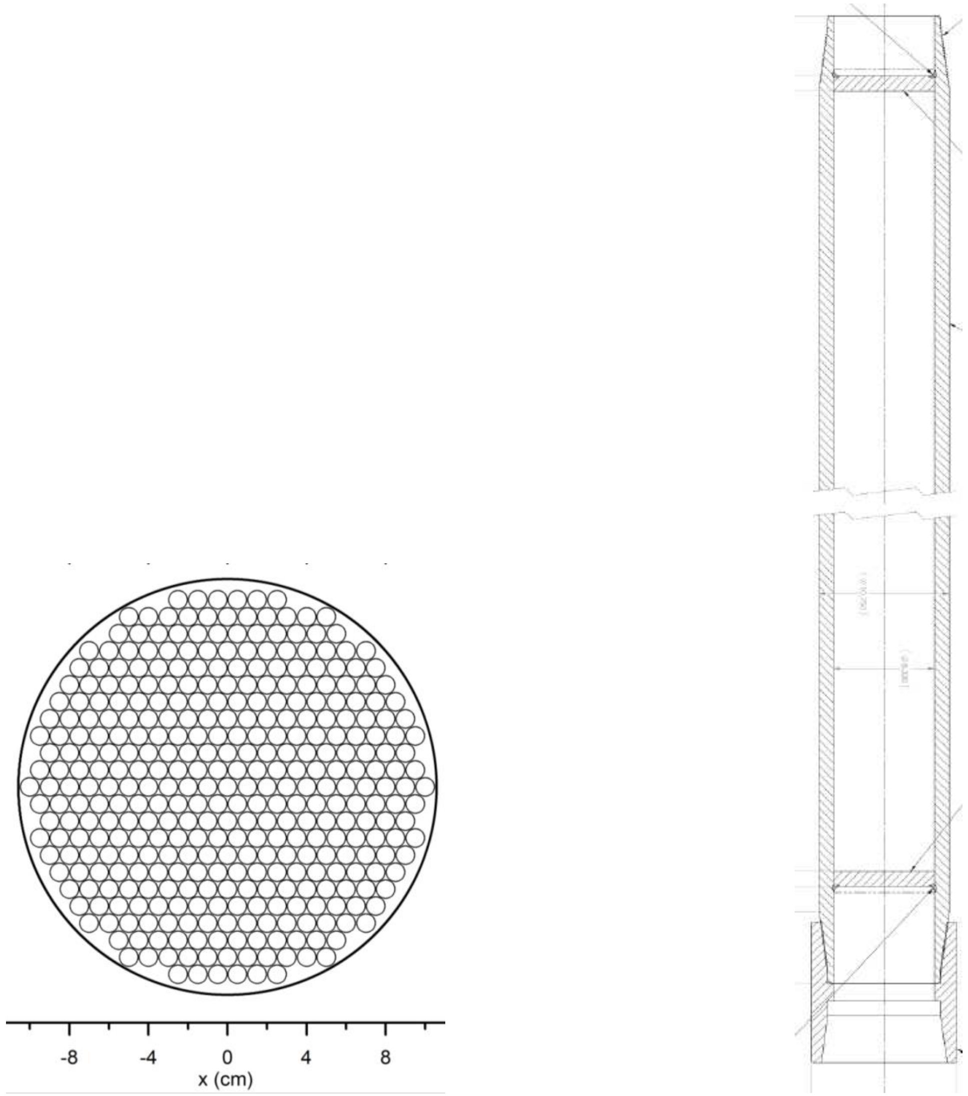

Figure 5. Left: Potential loading of Fuel Pins in a borehole waste canister, radial cross-section (Figure 5 of Arnold et al. 2011); Right: longitudinal cross-section through borehole waste canister (figures 5 & 6 of Arnold et al. 2011). Not to scale; diameters are the same for both.

Technical Requirements of the Reference Design

The information below is taken from (Arnold B. W., et al., 2011).

- Borehole is drilled and completed to a depth of about 5,000 m with the waste disposal zone located between 3,000 and 5,000 m depth in crystalline rock.
- Borehole and casing system must have sufficient stability and durability to provide a high level of assurance that waste canisters can be emplaced at the desired depth, with minimal probability of canisters becoming stuck during emplacement.
- Borehole and casing must have sufficiently large diameter to accommodate emplacement of test canisters.

- Deviation of the borehole from its designed trajectory must be controlled such that the distance between any two boreholes is greater than 50 m at a bottom depth of 5,000 m. Modeling has shown the thermal interference between disposal boreholes is relatively small for spacing of greater than 50 m. Drilling of multiple boreholes in an array must preclude the possibility of intercepting another borehole in which waste has already been emplaced. The spacing of waste disposal intervals at sites with multiple boreholes must meet thermal management requirements for disposal.
- Borehole and casing system must be designed such that casing can be removed from intervals where borehole seals are to be set. Optimal performance of borehole seals requires direct contact between seals and borehole wall.
- Casing and grout in the waste disposal zone must allow thermal expansion of fluid and flow into surrounding host rock to avoid over-pressurizing the fluid surrounding waste canisters.
- Drilling and borehole construction must be conducted to allow characterization of host rock in the waste disposal zone prior to waste emplacement.
- Borehole and casing system must have sufficient stability and durability to allow retrieval of waste canisters during the operational period, if necessary. The operational period is defined as the time until all borehole seals are emplaced and surface abandonment of the borehole is completed.

DBD Design and Cost Considerations

Estimates for the cost of borehole disposal depends on numerous design criteria, including depth, diameter, other design criteria (e.g., liners, fillers, lubricants, etc.), number of canisters emplaced in each borehole, the number of boreholes required (e.g., to accommodate all SNF in a country), how canisters would be constructed, packaged, and transported, as well as methods for closing, backfilling and sealing each borehole. The figures below are provided as an example, and are consistent with estimates provided by (Arnold B. W., et al., 2011).

Table A. DBD operational estimates.

Borehole Capacity	400 waste canisters (approx.)	
Canister capacity	0.2 MTU* 0.6 MTU	Single assembly (BWR) Consolidated pins
Operational time	~ 6 months per borehole	Includes drilling, emplacement, final sealing.
Cost per borehole	~ $40M USD	2011 estimate
Total facility capacity (multiple boreholes)	50 – 150 boreholes 20 – 40 boreholes	USA Sweden
Total Cost for DBD facilities above	$2B – $6B USD (USA) 0.8B – $1.8B USD (Sweden)	Cf. $50B USD for Yucca Mtn. Cf. $2B USD for Forsmark KBS-3
Total operational time for multiple borehole facility	25 – 75 years operations	does not include site selection

* MTU: Metric tonnes (1,000 kg) of uranium (equivalent to uranium content before irradiation in a reactor; does not include mass of oxygen in SNF (UO_2) or the steel and other metals that make up the fuel assembly.

APPENDIX B: DOWN-HOLE INSPECTION EQUIPMENT

Some potential DIV-relevant technologies for verifying DBH design are described here. All items are commercial off-the-shelf (COTS) equipment used in the drilling industry. Some are used for down-hole inspection of borehole features, but most are used for well logging; that is, to reveal physical and other properties of rocks surrounding the borehole. These, especially, might require special modifications and other R&D to adapt them for safeguards use. Existing technologies currently used or being developed for DIV might also be modified to be used to verify down-hole design of a borehole. One possibility is the IR range-finder.

Most down-hole inspection tools use a “wireline” for down-hole access. A wireline is a cabling technology used by operators of oil and gas wells to lower equipment or measurement devices into a well or borehole. The oil and gas industry uses wireline logging to obtain information down hole. A 'logging tool' (or a string of one or more instruments) is attached to the end of a wireline and lowered into a borehole. Logging tools developed over the years measure the natural gamma ray emissions, electrical, acoustic, stimulated radioactive responses, electromagnetic, nuclear magnetic resonance, pressure, and other properties of the rocks and their contained fluids. Some such tools might be adaptable for use for DIV. These include:

- Optical imaging: downhole video cameras
- Acoustic imaging
- Electrical imaging
- Methods that draw on both acoustic and electrical imaging techniques using the same logging tool

Imaging

Optical imaging: Small cameras that can be lowered into a borehole to assess the condition of the casing. A digital image is viewed on a monitor screen at the surface and can be recorded on DVD.

Borehole diameter

Borehole diameter can be measured at depth by using calipers.

Caliper transducers consist of two or more piezoelectric-crystal stacks placed in the wall of the drill collar. These transducers generate a high-frequency acoustic signal, which is reflected by a nearby surface (ideally, the borehole wall). The quality of the reflection is determined by the acoustic-impedance mismatch between the original and reflected signals. Often, there are difficulties in obtaining caliper measurement in wells with high drilling-fluid weights. Compared to the wireline mechanical caliper, the ultrasonic caliper provides readings with much higher resolution.

Physical calipers: A tool that measures the diameter of the borehole, using either 2 or 4 arms, such as the Multi-Finger Caliper (Spartek Systems) which uses multiple steel calipers to measure the internal radius of wellbore tubing and casings.

Casing properties

A casing inspection log is an *in situ* record of casing thickness and integrity (commonly used to determine potential corrosion of the casing). The methodology may include a combination of measurements, including acoustic, electrical, and mechanical techniques, to evaluate casing thickness and other properties.

Magnetic Flux Leakage: A *Casing Inspection Tool* (Spartek Systems) is described by its manufacturer as using Magnetic Flux Leakage technology to determine changes in the pipe wall thickness, the same technology used to monitor pipelines. The technology can measure metal thicknesses in borehole casings both internally and externally.

An **eddy-current** measurement uses a high-frequency electrical signal induced in the casing to determine the effect of pits and holes in the inner wall of a casing. Eddy-current measurements are typically used in conjunction with a flux-leakage measurement to determine casing corrosion, the latter being sensitive to the defects on both the inner and outer walls. A transmitter coil produces a magnetic field that induces eddy currents in the casing wall. These currents generate their own magnetic field that induces a signal in two closely spaced receiver coils. In smooth casing, these signals are the same, but variations give signals that are different (e.g., corrosion pitting, pipe-diameter differences, disparate pipe materials, etc.). Transmitter-receiver combinations are placed on multiple pads applied against the casing at several azimuths to fully cover the casing wall.

Properties of drilling mud, cement, down-hole lubricant, etc.

A **cement bond tool**, or CBT, is an acoustic tool used to measure the quality of the cement behind the casing. The methodology uses variations in amplitude from an acoustic signal traveling down the casing wall between a transmitter and receiver to determine the quality of cement bond on the exterior casing wall. Using a CBT, the bond between the casing and cement as well as the bond between cement and formation can be determined. The acoustic signal is attenuated more by casing cement than by un-cemented casing. The measurement is largely qualitative.

A technique similar to that of a CBT is **Pulse-Echo**. This technique uses ultrasonic transducer in transmit mode to emit a high-frequency acoustic pulse towards the borehole wall. The pulse is reflected back to the same transducer operating in receive mode. The measurement consists of the amplitude of the received signal, the time between emission and reception, and sometimes the full waveform received. Tools that use this technique either have multiple transducers, facing in different directions, or rotate the transducer while making measurements, thereby obtaining a full image of the borehole wall. Pulse-echo techniques are used in the borehole televiewer. In cased hole, the waveform is analyzed to give indications of cement-bond quality and casing corrosion.

Fluid-density log is a record of the density, or changes in density, of fluids in a production or injection well. Since gas, oil and water all have different densities, the log can determine the percentage, or holdup, of the different fluids, directly in the case of biphasic flow, and in combination with other measurements for triphasic flow. Fluid density is measured by a gradiomanometer or a nuclear fluid densimeter, and can also be derived from the depth derivative of a pressure sensor. This might be applied to identifying/verifying down-hole lubricants and similar features.

A **photon log** is a record of the density in and around a completed well using a radioactive source of gamma rays and a detector. The log is recorded with a **nuclear fluid densimeter**, a device for measuring the density of fluids in a completed well by using a radioactive source of gamma rays and a detector. In most instruments, a ^{137}Cs (cesium) or ^{241}Am (americium) source is used to induce Compton scattering, as in the open-hole density measurement, except that the device is unfocused. The count rate at the detector then depends primarily on the density of the fluids in the well. In some devices, the fluids pass through an open space in the body of the tool within which the measurement is made. The results then reflect the density of the fluids passing through the tool. In other devices, the source and detector are isolated so that the gamma rays pass outside the tool. The results then reflect some average density of all the fluids within the well.

Spectral noise logging (SNL) is an acoustic noise measuring technique used in oil and gas wells for well integrity analysis, identification of production and injection intervals and hydrodynamic characterization of the reservoir. SNL[13] records acoustic noise generated by fluid or gas flow through the reservoir or leaks in down-hole well components.

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[13] Not to be confused with Sandia National Laboratories.

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