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Design Verification for Deep Boreholes – A Scoping Study

Robert J. Finch, Heidi Smartt, Risa Haddal

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

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Robert J. Finch, Heidi Smartt, Risa Haddal

Sandia National Laboratories

P. O. Box 5800

Albuquerque, New Mexico 87185-MS1371

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. DBD presents some distinct challenges for safeguards compared to a conventional mined geological repository (MGR), including the ability to verify declared design information about the borehole. The ability to verify a borehole's design is crucial for assuring that spent fuel or other accountable nuclear materials are disposed as declared in a borehole of known and verifiable design.

This study reviews existing commercial off-the-shelf (COTS) borehole inspection tools currently used by the drilling industry, and evaluates the capabilities of those COTS inspection tools against how well they can meet potential needs and requirements of Design Information Verification (DIV) inspections for international safeguards. The study provides recommendations for several promising COTS borehole inspection tools that might be used for DIV safeguards inspections and recommends possible modifications and future testing.

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EXECUTIVE SUMMARY

Disposal of nuclear and radioactive wastes in deep boreholes (3-5 km) has been examined as a possible alternative to mined geological disposal. Unlike mined repositories, a deep borehole (DBH) is inaccessible to humans and cannot be inspected directly. A recent study of safeguards considerations for deep borehole disposal (DBD) identified challenges to verifying a deep borehole's declared design through safeguards inspections known as design information verification (DIV). These challenges are due in part to the lack of inspection tools available for DIV inspections of DBHs. We review in this report commercial off-the-shelf (COTS) borehole-inspection tools currently used by the drilling industry, and evaluate capabilities of those COTS inspection tools against how they might meet requirements for DIV inspections of DBHs. While the overarching focus of this survey is on tools for inspecting individual boreholes, design features relevant to DIV of a DBD facility are also addressed.

Key design features of a DBD facility of interest for DIV inspections include (1) waste-canister design; (2) design, construction and use of surface facilities; (3) design features relevant to a DBD facility's operations and closure, including seals used to close and permanently seal individual boreholes; (4) the layout of borehole arrays (if applicable); and (5) the design and construction of individual boreholes.

Specific borehole design features of interest for DIV include a borehole's depth, trajectory, geometry, and distance from adjacent boreholes, as well as certain casing properties (diameter, material properties) and plans and design criteria for potentially retrieving emplaced waste canisters. DIV tools should be able to detect deviations from declared borehole design, including changes in the above parameters as well as the ability to detect side holes, unexplained gaps in casing and borehole cement, undeclared changes to, or substitutions for, declared casing materials, and any undeclared features that might be hidden behind removable casing or other obstructions.

Key Findings

A large variety of COTS borehole inspection and logging tools are available, and their use is both extensive and routine in the field. Many commercial uses for these tools apply directly to achieving safeguards-relevant DIV objectives, such as inspecting casing and cement properties, borehole and casing diameters, and borehole trajectory. Other applications relevant to DIV inspections may require specialized testing, modifications, or both. Capabilities relevant to these non-standard safeguards applications mostly involve identifying and locating undeclared design features, including those that might be hidden behind installed casing. For example, inspection tools will be needed that can identify hidden side holes (dog legs) or other design variations such as undeclared high-strength, corrosion-resistant casing or casing with larger-than-specified diameter (potentially hidden behind smaller-diameter, removable casing). The first of these (side holes) could indicate undeclared shallow storage for waste canisters to be recovered later; the latter (variations in declared casing design) are potentially indicative of plans for retrieving waste canisters after emplacement.

Broadly speaking, borehole-inspection tools are used either during drilling (known as measurement while drilling [MWD] and logging while drilling [LWD]) or after drilling has been completed, before or after borehole casing has been fully installed (or both). The drilling contractor (or operator) commonly uses MWD and/or LWD to monitor and evaluate drilling progress, including borehole trajectory, among other objectives. A DIV inspection might be able to use inspection tools employed, or data obtained, by the operator during drilling (with appropriate joint-use protocols and data/signal branching, encryption and authentication, as necessary); however, we assume in most of this report that DIV inspections will be

performed on completed boreholes using IAEA-dedicated inspection tools, although using certain operator-owned equipment may be unavoidable, most notably hoisting, hauling and wireline equipment for handling and operating borehole-inspection instruments.

Most borehole-inspection tools evaluated for this report are designed to operate in a borehole that contains a fluid, most commonly drilling mud; however, if DIV inspections are restricted to being conducted after each borehole is completed and fully cased, DIV inspections could be limited to using only instruments that can operate in air. For this reason, we emphasize equipment that can operate in air, including some equipment that is designed for use in shallow boreholes (less than 2,000 m) or at temperatures and pressures lower than expected near the bottom of a 5 km-deep borehole. Such equipment would likely need modifications to their designs (or add-on equipment) to make them useful at DBH depths. Nevertheless, depending on drilling technology and other specifics of individual borehole construction, fluids may be present during borehole inspections (or might be added for that purpose), and many fluid-dependent instruments are included in this report. Indeed, because some information of interest for DIV inspections might only be obtained from these fluid-dependent instruments, conducting DIV inspections in fluid-filled boreholes might be an imperative. The table below lists COTS tools that might be used to glean information relevant to DIV inspections according to ambient borehole environment (air or fluid) in which these tools can operate.

Potential DIV inspection tools and applicable borehole environments

Inspection parameter	Air & Clear Water	Drilling Mud
Borehole images	Optical video cameras Optical Televiewers	Acoustic Televiewers
Casing/Borehole Diameter	Multi-finger Calipers	Multi-finger Calipers Acoustic & (most) EM scanners
Casing & Cement properties*	Magnetic flux leakage tools (casing thickness) (some) electromagnetic scanners	MFL ultrasonic cement-bond logging tools
Borehole trajectory	Multi-finger Calipers w/ inclinometer Gyroscopes Magnetometers (w/o casing)	Multi-finger Calipers w/ inclinometer Gyroscopes Magnetometers (w/o casing)

* An evaluation of cement properties (cement-bond logging) might reveal hidden gaps or side holes.

Recommendations

Determine DIV inspection requirements and contingency plans. In order to identify the most appropriate tools for use in a DIV inspection, inspection requirements need to be established. For example, will a survey of the completed borehole with installed casing provide sufficient information for an unambiguous conclusion to be drawn? Will information about a borehole’s construction be needed before completion? If so, how is that information to be obtained (e.g., sharing operator equipment during MWD or interrupting drilling operations for independent inspections)? If a question arises from DIV information obtained, what additional information will be needed to draw a firm conclusion? What additional equipment (or different survey methodology) can obtain the necessary information? Answers to

questions such as these will help determine which tools are needed to provide necessary information at the appropriate time.

We have tacitly assumed for this report that DIV inspections are likely to be performed after a borehole has been completed and the casing installed. The environment considered most likely during a post-completion DIV inspection is an air-filled borehole, severely limiting tools available for in-depth examination of casing and cement properties (potentially making the detection of gaps or side holes more challenging). An operator's drilling plans could impact such an assumption. For example, if a borehole is drilled with the use of drilling mud, a DIV inspection might be performed before the mud is removed, using appropriate acoustic and electromagnetic (EM) scanners; then a final (separate) optical inspection of the borehole might be conducted after mud has been removed.

Use compatible instruments in a single down-hole inspection tool when possible. Because of the time and effort associated with handling borehole inspection equipment (including hauling from on-site storage to a borehole and lowering on a wireline) a single downhole probe with multiple inspection tools is desirable, maximizing information gleaned from a single inspection survey or trip.

For example, if inspecting an air-filled borehole after completion, we recommend a multi-finger caliper (MFC) equipped with optical video camera plus inclinometer. Such a tool would provide visual information about the inner casing while recording casing diameter and inclination. The possibility of including a magnetic flux leakage (MFL) tool with air-capable EM scanner on the same probe would further increase efficiency and provide additional information about casing properties (thickness, gaps and material properties) as well as identifying gaps behind casing. It is unclear from our analysis that such a multi-tool is feasible (this would need confirmation from tool suppliers), but it is not uncommon to deploy more than one instrument in a single wireline trip.

Use operator-owned hauling, hoisting and wireline equipment. COTS tool weights can range from a few tens of kg to more than 100 kg, and tool lengths can reach 5 or 10 m (or more), making the handling of most inspection tools by individuals difficult or impossible, and potentially dangerous. Most COTS inspection tools require special hoisting and hauling equipment; however, such equipment is likely to be available at the drilling site, owned or leased by the drilling operator. Rather than purchasing hoisting and hauling equipment for dedicated use by DIV inspectors, entering an agreement with the operator to share such equipment seems a clear choice, especially as such equipment does not impact measurements. In addition, most inspection tools evaluated for this report are deployed downhole on a wireline (or slick line), also likely to be in use on site by the operator. Shared use of wireline that contains telemetry for communications may require special arrangements or modifications for inspection tools using a shared wireline. Where possible, tools that store data in memory downhole for later downloading to a computer at the surface are recommended for DIV inspections.

Combine remote sensing at a DBD facility with DIV inspections of individual boreholes. The ability to detect all possible undeclared design features in a completed borehole is unlikely to be straightforward, even with state-of-the-art inspection tools. Remote sensing of drilling activities during the construction and operation of a DBD facility can provide additional assurance about the absence of undeclared design variations and improve confidence in the ability to detect them. Seismic/acoustic monitoring of drilling activities, in particular, is recommended as a complement to individual borehole inspection.

Consult with borehole inspection-service providers. Many borehole-inspection tools evaluated for this report use technologies that require special knowledge and training to operate safely and effectively and

to interpret data appropriately. Numerous borehole logging and inspection services are available, and these have expertise and experience with a wide variety of borehole evaluations.¹ We recommend that the inspectorate consult one or more such service providers for advice on tool use and possible for training DIV inspectors.

This recommendation brings us to another possibility, which is to out-source DIV inspections to an independent service provider.

Alternative Option: Use a commercial logging and borehole-inspection service for DIV inspections.

Given the number of companies that provide professional borehole logging and inspection services, combined with training, handling and other requirements for proper tool use, it seems prudent to explore the possibility of hiring a well-logging service provider with appropriate experience and expertise to conduct DIV inspections. This may break from existing DIV safeguards practice and would require appropriate arrangements. Nevertheless, if possible to implement, this option could significantly increase confidence in obtaining reliable DIV information with minimal effort, delay or disruption in the field.

Explore novel technologies for DIV inspections of deep boreholes. Despite the range and variety of COTS borehole inspection and logging tools, certain unique demands for DIV inspections may not be fully addressed by current COTS technologies, as some tools might be used to glean information they are not really designed to extract. Applying technologies used for other applications to borehole DIV inspections could prove promising. For example, ground-penetrating radar might effectually detect gaps and side holes in an air-filled borehole, provided such equipment could be integrated into a downhole probe. Another example might be to develop a modified IR (infra-red) range finder to probe borehole diameter or other casing features of interest for DIV inspections. In fact, testing COTS borehole-inspection tools under realistic condition could reveal potential gaps in DIV information.

¹ A list of well-logging service companies is available from the Oildex web site (<https://www.oildex.com/resources/directory/service-companies/#well-logging>), although no attempt was made by us to assure all information on that site is correct or complete.

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NOMENCLATURE

ABBREVIATIONS

AP	additional protocol
ATV	acoustic televiewer
BHA	bottom hole assembly
BWR	boiling water reactor
CBL	cement-bond log
CCD	charge-coupled device
CMOS	complementary metal-oxide semiconductor
CoK	continuity of knowledge
COTS	commercial off the shelf
CSA	comprehensive safeguards agreement
C/S	containment and surveillance
DBD	deep borehole disposal
DBH	deep borehole
DHV	down-hole video
DIV	design information verification
DVD	digital video disk
EM	electromagnetic
EMF	electromotive force
GR	gamma ray log
HLW	high-level waste
Hz	Hertz
IAEA	International Atomic Energy Agency
ID	inside (or inner) diameter
LCD	liquid crystal diode
LWD	logging while drilling
LWR	light water reactor
MD	measured depth
MEMS	Microelectromechanical system
MFC	multi-finger caliper
MFL	magnetic flux leakage
MGR	mined geological repository
MPa	megapascal (pressure unit)
MWD	measurements while drilling
MTT	magnetic thickness tool
OD	outside diameter
OTV	optical televiewer (also OPTV)
PWR	pressurized water reactor
SNF	spent nuclear fuel (also “used nuclear fuel”)
TID	tamper-indicating device
TIE	tamper-indicating enclosure
TVD	true vertical depth
UPS	uninterrupted power supply

GLOSSARY

Accelerometer	Device used to measure acceleration (the change of velocity with time) which is, in the context of borehole inspections, the acceleration due to gravity.
Attenuation	The decrease in amplitude or frequency (energy level) of energy caused by absorption and scattering as the energy propagates through a medium.
Azimuth	In the context of logging, azimuth is the angle (measured clockwise) of deviation from a north reference of a well-path. Azimuth may also be expressed as the compass direction of the borehole path, as determined from a borehole survey.
Bottom hole assembly (BHA)	Equipment or tools at the bottom of tubing or a drill string.
Braided wireline	A strong type of wireline used in retrieving tools heavier than a slick line can handle. Electrical line is a braided wireline with a central conductor.
Caliper	Instrument used to measure borehole or casing diameter, either by using mechanical arms that touch the sides of a borehole or its casing, or by using an acoustic signal that is echoed from the borehole wall, tubing and/or casing
Caliper log	A recording of borehole diameter made by using a caliper , either one that uses mechanical arms that touch the sides of a borehole or its casing, or that uses an acoustic signal that is echoed from the borehole wall, tubing and/or casing .
Capacitance	The ability (capacity) of a system to store an electric charge, measured as the ratio of a change in electric charge in a system relative to the corresponding change in its electric potential or voltage .
Cartridge	Section of a wireline logging/inspection tool that contains telemetry , electronics and power supplies.
Cased-hole log	Any of several logs (data records) obtained from measurements in a cased-hole environment (as opposed to an open hole without casing).
Casing	One of several strings of steel pipe in a borehole that stabilizes the borehole and forms a barrier to fluid movement into and/or along the drilled hole. Casing is commonly, at least partly, cemented in the borehole. Also “casing string.”
Casing shoe	The bottom of the casing string, including the cement around it, or the equipment run at the bottom of the casing string.
Declination	Angular difference between magnetic north and true (geographic) North.
Directional drilling	Drilling the borehole in a planned trajectory.
Dog leg	An abrupt change in the direction of a borehole, commonly reported as degrees per 100 ft.
Drill string	All the equipment in a drilling bottom hole assembly (BHA) plus the drill pipe.

Drilling mud	Liquid and gaseous fluids and mixtures of fluids and solids (as solid suspensions, mixtures and emulsions of liquids, gases and solids) used for borehole-drilling operations. Drilling muds can be classified according to composition and function: (1) water-based, (2) non-water-based (e.g., oil-based), and (3) gaseous (pneumatic); however, categories can overlap.
Drilling fluid	Drilling mud
Eddy current	A loop of electrical current in a conductor induced by a changing magnetic field.
Electromotive force (EMF)	The difference in potential (voltage) that tends to give rise to a current.
Formation	A group of rocks related by common lithology or other distinguishing features.
Frequency	Number of [wave] repeats per unit time, also called cyclic frequency. Angular frequency (ω) is measured in radians per unit time with magnitude equal to 2π multiplied by the cyclic frequency (<i>cf.</i> Hertz).
Gamma ray log (GR)	A measure of naturally occurring and artificially induced gamma-ray radiation, most commonly obtained by using a scintillation crystal and photomultiplier tube. Also the data record of such measurements.
Hole Direction	The horizontal component of a borehole, generally measured as the angle (azimuth) that the axis of the borehole (or survey instrument) deviates from a north reference.
Hertz (Hz)	repeats or cycles per second (measured in units of sec^{-1}); <i>cf.</i> Frequency .
Impedance	Opposition to the flow of current, expressed in ohms as resistance , capacitance or inductance .
Inclination	Measure of a well's deviation from vertical (measured with an inclinometer). An inclination of 0° is true vertical, and an inclination of 90° is horizontal.
Inductance	The property of an electric conductor or circuit that causes an electromotive force (EMF) to be generated that opposes a change of current flowing through it by generating a self-induced internal EMF as a result of a changing magnetic field.
Liner	In the context of casing , a liner is a partial string of pipe that does not run back to surface, and which may or may not be cemented. In the context of sand control, a liner is a perforated, drilled or slotted liner for formation control or to preserve borehole access.
Lithology	Characteristics of rocks; <i>lithologic</i> (adj.) concerning rock characteristics.
Log	(noun) A record of data collected from a borehole. (verb) To systematically collect data from a borehole, usually measurement data obtained from specialized equipment.
Logging while drilling (LWD)	A technique that uses a suite of logs as part of the drilling bottom hole assembly (BHA) to obtain formation properties while drilling (commonly 40 to 60 feet back from the drill bit).

Lubricant	Material used to reduce drilling torque and drag (e.g., oil, synthetic polymers, graphite, glycols, glycerine).
Magnetic flux leakage (MFL)	Distortion of a magnetic flux introduced into casing by a low- frequency electromagnet or permanent magnet; sensitive to casing-wall thickness changes and defects.
Magnetic thickness tool (MTT)	Instrument that uses an alternating magnetic wave to measure casing -wall thickness.
Magnetometer	Instrument used to measure the intensity and variance of Earth's magnetic field.
Measured depth (MD)	Measured depth of a hole drilled to any point along (parallel to) the borehole, or to total depth, as measured from the top of the borehole at the surface; <i>cf.</i> true vertical depth .
Measurements-while-drilling (MWD)	The evaluation of physical properties, usually including pressure, temperature and borehole trajectory in three-dimensional space, while actively drilling a borehole (standard practice in offshore directional wells).
Microelectromechanical system (MEMS)	Micron-scale to millimeter-scale mechanical devices (< 0.1 to 1.0 mm) commonly used as components in accelerometers and gyroscopes.
Mud	Drilling mud
Multi-lateral borehole	Multiple boreholes emanating from a single borehole at the surface.
Mud log	(noun) A data record (also <i>well log</i>) of a borehole obtained by examining rock cuttings brought to the surface by the drilling medium, most commonly drilling mud , and exclusive of data obtained from down-hole instruments (the term appears to be losing currency). (verb) The act of collecting such data (<i>mud logging</i>).
Multi Shot	An instrument that can perform multiple surveys per trip downhole, and commonly used to control survey frequency. Multi-shot instruments are commonly used to fully characterize a borehole by obtaining data at multiple positions (stations) downhole.
Resistance (R)	Opposition to the flow of current through a material, expressed in ohms.
Rugosity	Qualitative description of borehole-wall roughness or changes in borehole diameter. In borehole logging, the term usually refers to changes at the scale of logging measurements of a few inches to a few feet, and to the effect this has on logging-tool response.
Run	Operation in which a logging tool is lowered into a borehole and then retrieved from the borehole while recording measurements.
Single Shot	An instrument used to perform only one survey per trip into a borehole, commonly used for periodic inspections of borehole progress (depth, course, position) during drilling; <i>cf.</i> multi-shot .
Slick line	Small solid wire used for rapid, economic placement and retrieval of small equipment in a borehole.
Sonde	Section of a logging/inspection tool that contains measurement sensors.

Spontaneous potential log	Measurement of the voltage (potential) difference between a rock formation and fluid in a borehole. Such voltage differences arise due to salinity differences between a formation and borehole fluids.
Telemetry	Communications process (commonly automated) by which data collected at remote or inaccessible points are transmitted to receiving equipment; e.g., transmission of data from down-hole instruments to a computer at the surface.
Tie-back	Casing that connects a downhole liner to the surface with a casing of similar size.
Trip	Pulling all pipe from the borehole and rerunning the pipe to bottom.
Trip in	A run into (down) a hole with tubing or drill pipe.
Trip out	To pull a string of tubing or drill pipe out of a hole.
True vertical depth (TVD)	The distance from the surface to the bottom of a borehole, measured perpendicular to the surface; cf. measured depth .
Tubular	General term for any borehole pipe or casing . Typically, it refers to the smaller, inner string of casing or pipe in a borehole (for fluid flow in a production well); also tubing.
Ultrasound	High- frequency sound (greater than 20,000 Hz) undetectable by human hearing.
Voltage	The difference in electric potential energy between two points per unit electric charge. The voltage between two points is equal to the work needed to move a unit charge against a static electric field; measured in units of volts (one joule per coulomb). Also referred to as electric potential difference, electric pressure or electric tension.
Wave train	Elastic response of a material to an energy impulse (commonly acoustic energy in the context of borehole inspection).
Well bore	A drilled hole; synonymous with borehole.
Wireline	A cable used to lower items (e.g., inspection tools) into a borehole, and which can be used to obtain a log by using an electrical cable for power and to transmit data to the surface (<i>cf.</i> measurements while drilling (MWD) and mud logging).

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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. And while the primary benefits of DBD could be increased safety, reduced cost, and greater flexibility (Brady & Driscoll, 2010; Bates, Driscoll, Lester, & Arnold, 2014), the method could also impact the implementation of international safeguards.

The IAEA performs inspections to assure a nuclear facility under safeguards is being used as declared and lacks undeclared capabilities, including design information verification (DIV) inspections. DIV inspections are conducted during a facility's construction and throughout its lifetime. Because a facility for the disposal of spent fuel is a nuclear facility subject to safeguards, DIV inspections will be performed at disposal facilities, including DBD facilities.²

A recent study of safeguards considerations for DBD identified some challenges in verifying a borehole's declared design by means of DIV inspections, due in part to the lack of suitable tools available for DIV inspections of deep boreholes (Finch, Haddal, & Baldwin, 2016). That report suggested examining the feasibility of employing borehole inspection tools currently used by the drilling industry. Following up on that suggestion, the current report reviews existing commercial off-the-shelf (COTS) borehole-inspection tools currently used by the drilling industry. This study surveys COTS borehole inspection tools that show promise as potential tools for DIV safeguards inspections, possibly with modifications, and includes recommendations for testing these tools for safeguards DIV.

The drilling industry is vast, supporting exploration for and production of oil, gas, mineral, and water resources, as well as geothermal energy. This wide range of drilling applications has resulted in a large variety of drilling activities and well or borehole designs and practices. Such variety of applications and designs means the number and variety of borehole-inspection tools is similarly vast. This report, therefore, provides a survey of tools and manufacturers that is not, and is not intended to be, comprehensive; rather, it provides a sampling of available technologies in current use by the drilling industry, selected for their potential application for DIV inspections of a DBD facility.

² Note that, in the context of SNF or HLW disposal, 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 for Sweden and Finland (SKB 2010) or Germany (Bollingerfehr, et al. 2013). Neither should "deep boreholes" in this context be confused with the IAEA's BOSS concept for the disposal of sealed radioactive sources, for which boreholes are up to about two orders of magnitude shallower (IAEA 2009).

2. DEEP BOREHOLE DISPOSAL

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 HLW in the lower 2,000 m of the borehole, 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).³ Multiple boreholes might be constructed at one disposal site, with spacing between boreholes determined by thermal loading and other safety factors. The concept is illustrated in Figure 1, 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 might 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, DBD faces engineering challenges (NWTRB, 2013; Beswick, Gibb, & Travis, 2014).

A reference design for a DBD system has been described (Arnold B. W., et al., 2011). According to that design, 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. In order to help prevent potential crushing of underlying canisters during the operational period, bridge plugs would be placed between emplaced canisters at specified intervals. 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 plugs, depending on the specific design (Figure 2). Additional information about technical requirements for the reference borehole design can be found in Appendix A and in the original report (B. W. Arnold, et al. 2011).

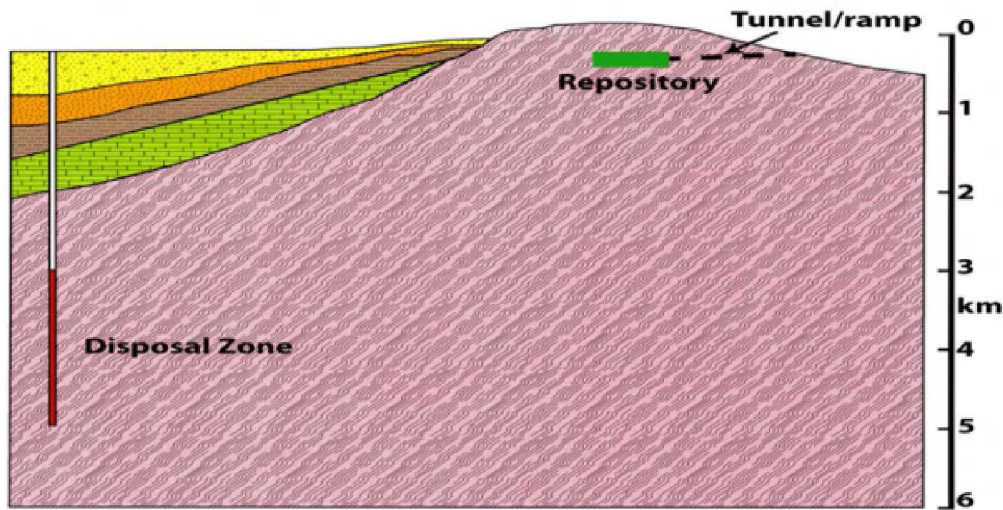


Figure 1. Schematic diagram of the deep borehole disposal concept (“disposal zone” at left) compared with a conventional mined geological repository (“repository” at right); figure from (NWTRB, 2013).

³ Specific dimensions refer to the borehole reference design used for this report (B. W. Arnold, et al. 2011) and may differ from any particular or proposed borehole design.

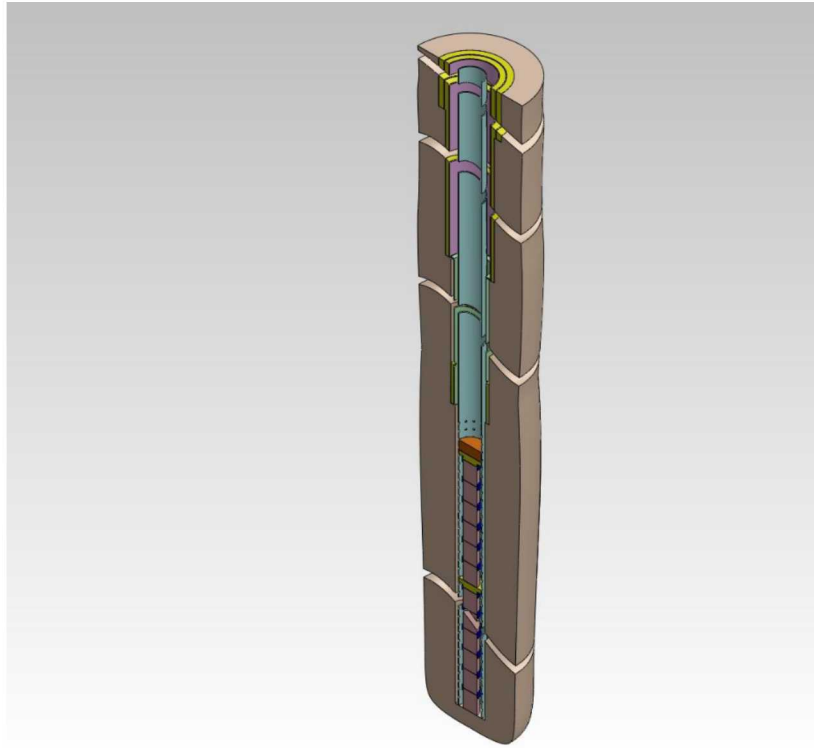


Figure 2. Schematic depiction of a completed borehole. Not to scale; borehole seals not shown (cf. Figure 4). Configuration shown is after waste has been emplaced and the overlying cement plug has been set, but before the casing has been cut and removed; from Figure 3 in (Arnold B. W., et al., 2011, p. 24).

3. DESIGN-INFORMATION NEEDS FOR DBD FACILITIES

The IAEA has examined safeguards for conventional MGRs, and a review of IAEA policy and recommendations for MGRs provides a basis upon which to examine potential special considerations for DBD. Based on IAEA policy (IAEA, 2003) and model integrated safeguards approaches being developed by the IAEA (IAEA, 2010), the safeguards system for disposal facilities must be able to, among other things, verify design information throughout the life of a disposal facility (including design, construction, and operation).

The IAEA continues to consider the application of these criteria to conventional MGRs but has not considered their application to DBD concepts. Some ramifications of meeting these safeguards requirements for a potential DBD facility were examined in a recent report (Finch, Haddal, & Baldwin, 2016). DBD features relevant to DIV include borehole design and configuration, borehole casing, and borehole seals. In addition, the designs of disposal canisters and surface facilities at a DBD site are also of interest, along with emplacement operations and borehole and site closure. These are discussed in more detail below.

3.1. Borehole design

Numerous design features have relevance to a DBD system, including borehole depth, diameter (both hole and casing), waste canister size, the size of a borehole array (the number of individual boreholes located at a single DBD site), and spacing between boreholes. The following sections introduce key features and discuss their role in deep borehole design. The focus of this report is on design criteria for individual boreholes, although factors to consider for borehole arrays are also noted. The discussion draws heavily on design criteria for a specific reference borehole design (Arnold B. W., et al., 2011; Arnold B. W., et al., 2013). Exact specifications for any individual borehole design (planned or prospective) can differ; however, the reference borehole design referred to here is considered to be sufficiently representative for the purposes of this report.

3.1.1. Borehole Configuration

Although a DBD facility may include an array of multiple individual boreholes, the objective of this report is to survey tools used to inspect individual boreholes. Nevertheless, considerations for multiple borehole arrays and multi-lateral boreholes⁴ are noted below.

3.1.1.1. Borehole arrays

The DBD facility concept considered here comprises multiple boreholes located at a single DBD facility site with spacing between individual boreholes being on the order of 200 m (Arnold B. W., et al., 2013); the spacing is a function of thermal-management requirements for disposal. A country with a small to moderately sized nuclear power program (fewer than 20 reactors for example) might require between 20 and 40 boreholes (Finch, Haddal, & Baldwin, 2016), all of which could be collocated at one site covering an area of approximately one to two square kilometers.

⁴ Multi-lateral boreholes comprise multiple boreholes emanating from a single borehole at the surface.

3.1.1.2. Multi-lateral Boreholes and Directional Drilling

Multi-lateral boreholes are routinely used in the petroleum industry, and a fanned array of inclined or horizontal boreholes from a central borehole has been suggested for a DBD system (Gibbs, 2010). Such an approach might reduce drilling costs and a facility's surface footprint, but would likely increase the complexity of waste emplacement (Arnold B. W., et al., 2011). Nevertheless, the possibility of a borehole that deviates from a central borehole must be considered, and detecting any undeclared 'side' boreholes will be one objective during DIV inspections (Section 4). Recent progress in directional drilling makes this aspect of borehole DIV of special concern because this could facilitate subsequent (undeclared) retrieval of waste canisters from a deviated borehole. Such options could include side bores close to the surface or boreholes that are turned laterally at shallow depths. Either design might facilitate retrieval of canisters declared to have been emplaced much deeper. Borehole trajectory, directional drilling, and related surveys, are addressed further in Sections 4 and 5.5, and in Appendix C.

Overall borehole configuration, as well as drilling progress, direction and depth might be monitored remotely with established passive seismic/acoustic monitoring methods by using seismic/acoustic monitoring and recording stations to monitor drilling progress at a DBD facility. While this method is unlikely to verify detailed design features within a borehole, it could reveal deviations from declared borehole configurations sufficiently well to indicate a potential anomaly (e.g., lateral and/or branching boreholes) that might warrant more detailed inspection.

3.1.2. Casing

Casing is a major structural component of virtually any borehole, including deep boreholes. Among other things, casing helps maintain borehole stability and controls borehole pressure. Casing is a major part of the borehole design and its overall cost. The vast majority of casing used in the oil and gas drilling industry is manufactured of low-carbon steel (mild steel) usually alloyed with manganese, although other kinds of steel may be used (e.g., stainless). The strength of steel used for casing can vary, and certain applications may require more specialized steels.

The primary concern about borehole casing with respect to DIV inspections is likely to be casing material properties, especially strength and diameter, as these properties can influence options for retrieving emplaced waste canisters from within a borehole. Stronger more rigid casing could enhance retrievability of canisters by helping to ensure the casing retains its shape and acts as a resilient guide for down-hole retrieval tools. Other casing design features can factor into retrievability options, whether to facilitate retrievability or make it more difficult (see Section 3.5). Casing can also mask or obscure certain design features, such a dog leg or other deviations from a declared design. The ability to detect such features hidden by borehole casing would also be important for adequate DIV inspections (Section 4).

Several designs for deep-borehole casing have been proposed, including an uncased borehole in the disposal zone with removable casing in the seal zone (Woodward-Clyde Consultants, 1983), a perforated casing in the disposal zone for the penetration of grouts or sealing material into the annulus between outer surface of the casing and the borehole wall (Juhlin & Sandstedt, 1989), and an expandable casing in the disposal zone that is deformed outward to conform to the borehole wall by an oversized mandrel drawn upward through the casing (Beswick J. , 2008). We will not consider these alternative borehole designs in

this report, limiting our discussion to casing specifications for the reference borehole design (Table 1). First we introduce some casing terminology.

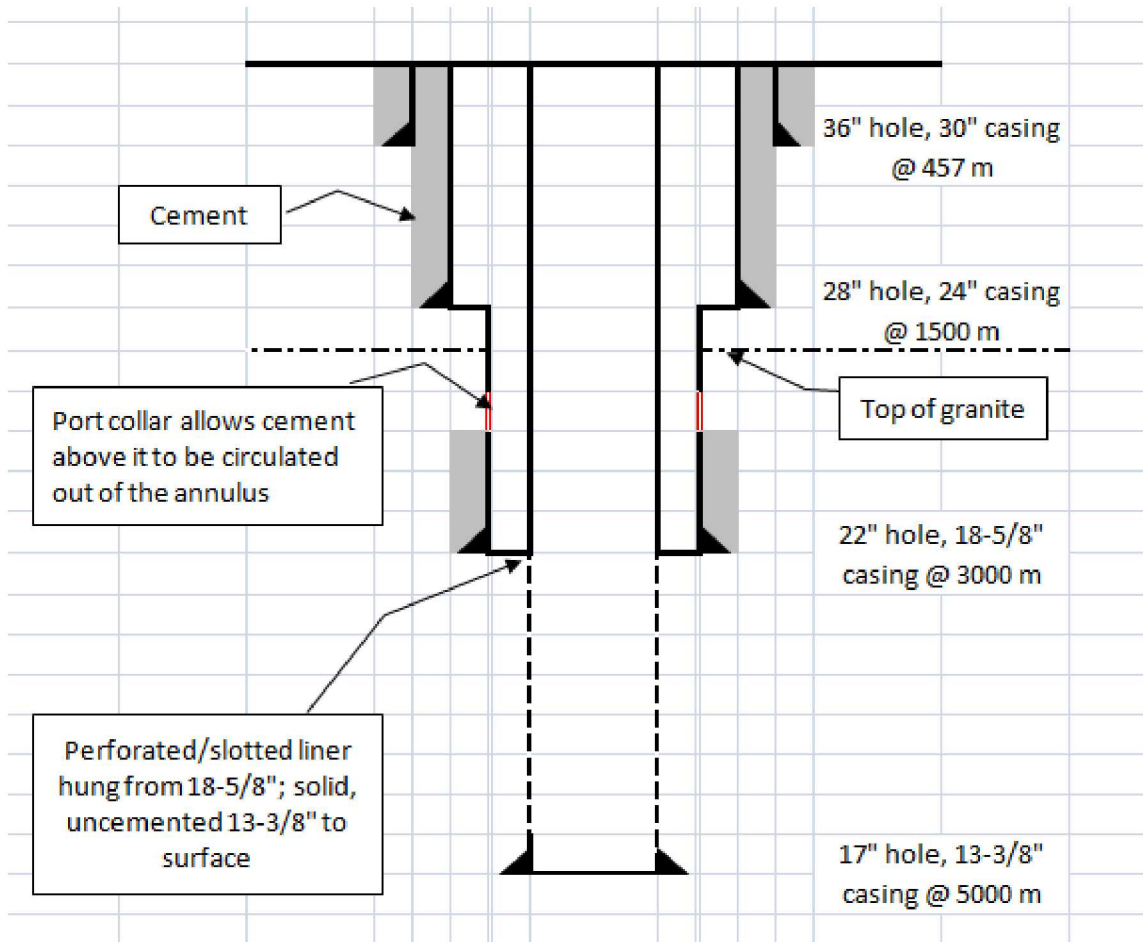


Figure 3. Illustration of drill-hole casings for the reference borehole design for waste disposal (B. W. Arnold, et al. 2011, Figure 4, p. 25).

In a conventional borehole, there are six basic types of Casing Strings: 1) *Conductor casing* is the first string set below the drive pipe, or structural casing. This is usually the string onto which the casing head is installed and is commonly cemented to the surface; 2) *Surface casing* provides a variety of protections and is used in deviated wells to cover the “build section” (curved section of a borehole) during deeper drilling. Surface casing is typically cemented to the surface; 3) *Intermediate casing* provides a variety of protections for production wells (there may be multiple intermediate casings, depending on the borehole); 4) *Production casing* is used to isolate production zones; 5) *Liner casing* does not extend back to the wellhead but is hung from another casing string and is typically cemented over its entire length; 6) *Tieback string* provides additional pressure integrity from the liner top to the wellhead.

The reference deep-borehole design includes five casing components: a surface casing, two intermediate casings, a liner and a guidance tieback (Figure 3). Proposed specifications for these casing components are provided in Table 1.

Table 1. Casing Specifications for a Reference Deep Borehole Design*

INTERVAL**	CASING OD (INCHES)	WALL THICKNESS (INCHES)	CASING ID (INCHES)	HOLE DIAMETER (INCHES)	WEIGHT (LB/FT)	TENSILE STRENGTH (PSI)
Surface	30	0.75	28.5	36	235	56,000
Intermediate 1	24	0.688	22.62	28	174	125,000
Intermediate 2	18.63	0.693	17.24	22	136	125,000
Guidance liner	13.38	0.38	12.62	17	54.5	56,000
Guidance tieback	13.38	0.38	12.62	17	54.5	56,000

* From (B. W. Arnold, et al. 2011, Table 2, p. 25).

** see Figure 3.

3.1.3. Borehole Seals

After closure, borehole seals (or plugs) constitute the primary component of the engineered-barrier safety system for the deep-borehole disposal concept (Arnold B. W., et al., 2013). After waste canisters have been emplaced and the overlying plugs have been set, the guide casing will be removed and the intermediate casing in the seal zone will be cut and removed. Seals and plugs in the seal zone will be seated in contact with the rock of the borehole walls. Seals made of compacted bentonite that swell when wet would be set by extrusion from a container or be emplaced by using a perforated tube. Cement seals, alternating with sand, crushed rock, and cement backfill, would fill the remainder of the seal zone (Figure 4 and Table 2).

Seals for final closure of a borehole are designed for safety purposes, and the degree to which seals put into place during borehole closure might impact subsequent retrieval is not well known. Certain design criteria could discourage or make more difficult subsequent re-drilling of a closed and sealed borehole in an attempt to retrieve emplaced waste canisters (National Academy of Sciences, 1994); this is addressed further in Section 3.5.

Although a State can declare the design of borehole closure seals, verifying the correctness of such a declaration after seals have been placed in the borehole would be a considerable challenge, if not impossible. No equipment examined as part of this report can be used to observe seals inside a sealed and closed borehole. Certain remote-sensing methods might permit some limited information to be gleaned about emplaced seals, a discussion of which would extend beyond the scope of this study. A reasonable option with current capabilities would be to verify seals (and/or the sealing material to be used) at the surface before they are installed in the borehole and possible supervision of their installation.

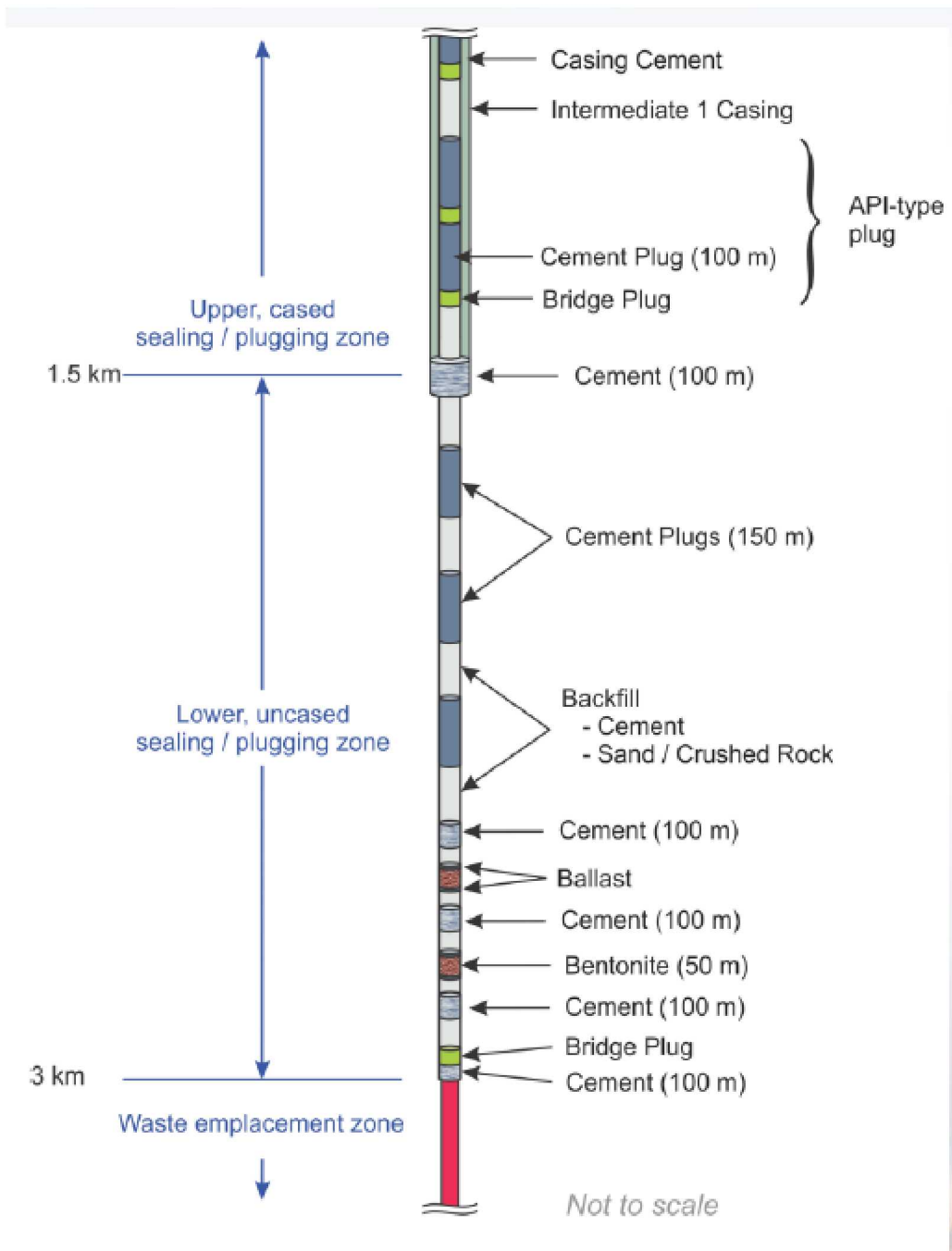


Figure 4. Safety Seals for reference borehole design (B. W. Arnold, et al. 2011, Figure 9, p. 46).

Table 2. Closure Safety Seals for Reference Deep Borehole Design*

Activity	Detail
Waste closure	Complete waste emplacement, pull Intermediate 2 casing, backfill to first keyed seal location.
First Seal	Cement lower section. Emplace lower sand buffer, then bentonite or bentonite-sand mixture, followed by an upper sand buffer. Cement upper section. Backfill to next seal location.
Second Seal	Cement lower section. Emplace lower sand buffer, then bentonite or bentonite-sand mixture, followed by an upper sand buffer. Cement upper section. Backfill to next seal location.
Third seal	Cement lower section. Emplace lower sand buffer, then bentonite or bentonite-sand mixture, followed by an upper sand buffer. Cement upper section. Backfill to first cement plug location.
First plug	Cement job.
Second plug	Cement job.
Third plug	Cement job.
Cement bottom Intermediate 1 casing	Cement job.
First API-type seal	Place lower bridge plug, continuous cement job for 30 m, place upper bridge plug, then second 30 m cement job. Backfill.
Second API-type seal	Place lower bridge plug, continuous cement job for 30 m, place upper bridge plug, then second 30 m cement job. Backfill.
Third API-type seal	Place lower bridge plug, continuous cement job for 30 m, place upper bridge plug, then second 30 m cement job. Backfill.

* From Table 4 of (B. W. Arnold, et al. 2011, p. 47); *cf.* Figure 4.

3.2. Canister Design

Waste canisters could be designed to facilitate retrieval by including hooks or other features to latch onto from above. However, canisters will already have some feature or features to permit lowering the canister into the borehole, and these same features could be used to extract emplaced canisters by reversing the emplacement process. This process of retrieving emplaced canisters will be tested in a proposed borehole engineering project (Arnold B. W., et al., 2013; MacKinnon, 2015).

In addition to such features, canister strength and size might also influence retrievability options. Stronger canisters could withstand greater stresses during extraction, and canisters with small diameters might be more readily extracted with existing equipment used by the industry for ‘fishing’ objects from a conventional borehole.

For DIV purposes, canister design specifications would be verified against a State’s declarations, most effectively by visual examination of unfilled canisters and reverification of canisters being emplaced (e.g., by canister identification markings or other verifiable characteristics).

3.3. Surface Facilities

As for a mined repository, a borehole disposal facility will require surface facilities for drilling and emplacement operations and equipment, receipt of and buffer storage for disposal canisters, administrative buildings, security barriers, etc. Verifying the design of surface facilities at a borehole facility is unlikely to present additional complications compared to DIV of surface facilities at a conventional MGR, and might, in fact, be somewhat simpler, depending on the scale of operations and facility design (Finch, Haddal, & Baldwin, 2016).

3.4. Borehole Operations and Closure

Before operations begin, activities are expected to be limited to site selection, facility design, and construction; no SNF will be received or located at the DBD site during this phase. Such activities fall within conventional DIV for nuclear facilities under IAEA safeguards; that is, until borehole construction begins.

Drilling an individual borehole to its design depth would be completed before emplacement of waste canisters. Emplacement operations would then proceed to completion before backfilling and sealing operations begin. For a DBD facility with a multiple-borehole array, individual boreholes may be in various states of operation: drilling, emplacement, closure and sealing, so that DIV inspections will be required for multiple boreholes, concurrently or consecutively. If a DBD facility includes multi-lateral boreholes stemming from a central borehole, drilling, emplacement, and backfilling of the individual branching boreholes might be performed before closing and sealing the central borehole. This could further complicate DIV inspections at such a DBD facility and would likely involve verifying each branching borehole to assure it has been constructed as declared before proceeding to emplacing canisters in adjacent branches.

Once a borehole has been filled to capacity, it is closed and sealed. Closure and sealing operations might include removing casing from the borehole and backfilling with a variety of materials, including specially designed seals, which, as noted (Section 3.1.3), will be difficult or impossible to verify after they have been installed. Post-closure monitoring of a DBD facility, after all boreholes at a DBD facility have been completed, closed and sealed, will be conducted by surveillance measures currently being developed for conventional MGRs (IAEA 2010, Mongiello, Finch and Baldwin 2013). Because safeguards on spent nuclear fuel remain in effect after disposal, a repository for spent fuel will remain subject to safeguards inspection, potentially including DIV inspections, indefinitely. Potential DIV inspections of closed sites would likely be limited (if performed) to verifying that the site remains undisturbed and in a state of final closure.

3.5. 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 a borehole can be retrieved. Some countries require that nuclear-waste disposal be demonstrably retrievable to varying extents (Haverkate, 2005), a requirement that could be reflected in borehole design. Nevertheless, as for mined repositories, a country that demonstrates the capability to drill a deep borehole and emplace waste canisters at depth, likely has the capability to retrieve that waste.

In the case of DBD, requiring retrievability of waste canisters might include designing disposal canisters to be accessible and recoverable from within the borehole, and that equipment for retrieving those canisters be available. Requiring retrievability might also include designing canisters to have longer lifetimes underground compared to disposal concepts for which no retrieval is envisioned (Harrison, 2000). Nevertheless, recovering disposal canisters not specifically designed for possible retrieval may make retrieval more difficult but not impossible (Nirex, 2004; Sapiie & Driscoll, 2009). Several 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), although the means to do so could seriously damage emplaced canisters, especially those not specifically designed for retrieval.

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 the retrieval of 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).

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).

Retrieving waste canisters from a closed and sealed borehole could involve re-drilling the borehole(s), an operation considered by one analysis to be relatively easy for sections filled with bentonite (National Academy of Sciences, 1994). 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 conducted after canisters had ruptured or corroded, a more complex approach with greater safety and health precautions would be required, but the US National Academy of Sciences (NAS) considered that emplaced waste would remain retrievable indefinitely at “somewhat greater cost” than during borehole operations (National Academy of Sciences, 1994). Retrieval might be made easier, if desired, through a variety of methods, including steel liners (see Casing Properties, Section 3.1.2) and down-hole lubricants (Sapiie & Driscoll, 2009).

To make retrieval more difficult, boreholes could be made harder to re-drill by embedding extremely hard material in the mud and concrete with which the hole is backfilled and sealed (see Section 3.1.3).

Verifying design features of backfill and seals after the borehole has been closed and sealed would be an unprecedented demand on DIV, as no known equipment could readily interrogate backfill and seals in a closed borehole. Attempts to access a borehole after closure will be almost certainly monitored by methods already being considered for a conventional MGR (Finch, Haddal, & Baldwin, 2016; Mongiello, Finch, & Baldwin, 2013) and drilling operations to retrieve nuclear material from a closed and sealed borehole would likely be a highly visible operation at the surface, so that a State might have difficulty retrieving nuclear material from a borehole without detection (National Academy of Sciences, 1994). Both borehole design and national policy on retrieval will be important factors when evaluating a State’s design declarations for a DBD facility.

3.6. Verifying Design Information

Design Information Verification (DIV) inspections are carried out by the IAEA at nuclear facilities to verify the correctness and completeness of design information provided by a State. An initial DIV inspection is performed on a newly built facility to confirm that the as-built facility is built as declared by the State. DIV inspections are performed periodically on existing facilities to confirm the continued validity of the design information and of the safeguards approach. The IAEA's authority for performing a DIV continues throughout a facility's lifecycle (see IAEA Safeguards Glossary, 3.30, pg. 27. IAEA 2001).

DIV is a crucial component of safeguards for any disposal facility. Design verification involves reviewing 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 and capabilities. According to IAEA Policy Paper 15 (IAEA, 2003), the State should provide to the IAEA as early as possible the following information about a proposed repository.

- 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, although content would likely differ dramatically on at least one point. Intended exploratory underground works, which for a DBD facility might include exploratory boreholes used to obtain rock cores and groundwater samples for site characterization, but not human-accessible ramps or tunnels.

During a DIV inspection, inspectors compare design information for a facility that the State has submitted to the IAEA with in-field observations to confirm that the information provided by the state is correct and complete, and that the facility has not been (or cannot be) misused.

Safeguards inspectors may visit declared facilities throughout a facility's lifecycle to verify safeguards-relevant design information. Such visits may be carried out during construction, during routine facility operations, following maintenance, and during decommissioning.

The IAEA routinely uses satellite imagery to evaluate information about a State's nuclear activities and to plan inspections, including complementary access under an additional protocol (AP), if applicable. Safeguards inspections during the operational phase of a DBD facility might include site inspections, seismic/acoustic monitoring, environmental monitoring, and overhead surveillance, in addition to DIV inspections of individual boreholes and surface facilities. Satellite imagery can provide little or no information about the design of deep boreholes, although surface facilities will be evident, and these may provide clues about potential undeclared designs or activities (Finch, Haddal, & Baldwin, 2016).

The ability to verify the design of a deep borehole to depths approaching 5,000 meters will present challenges, including the development of safeguards inspection tools for performing DIV inspections. Borehole DIV inspection tools will likely resemble borehole inspection equipment currently used by the

drilling industry, and several commercial off-the-shelf (COTS) borehole inspection tools are reviewed in Section 5. Such tools are not yet approved for use by the IAEA for safeguards-related DIV inspections, and would need to be tested and certified for eventual safeguards use before any country decides to begin construction of a DBD facility for spent fuel or other accountable nuclear materials.

Remote monitoring of borehole drilling might use surface-based seismic-acoustic monitoring to track underground progress and verify borehole configuration (Finch, Haddal, & Baldwin, 2016),⁵ much as envisioned for a conventional MGR (Mongiello, Finch, & Baldwin, 2013). While seismic-acoustic monitoring is not discussed further here, some COTS borehole inspection equipment might be used to follow up on information obtained from seismic-acoustic monitoring. The remainder of this report focusses on COTS borehole-inspection equipment currently used by the drilling industry for inspecting down-hole features.

⁵ “Configuration” means overall geometry, lateral, vertical, or branching, for example, rather than detailed design features such as casing materials or other internal features and materials.

4. BOREHOLE FEATURES OF INTEREST FOR DIV

Design specifications for a deep borehole can be complex, but a few key design features are likely of primary interest for DIV inspections. These include borehole orientation or configuration; casing properties, especially those that might indicate gaps or other features indicative of undeclared side boreholes or that could enhance retrievability; and integrity of cement that bonds the outer casing to the borehole wall, as gaps in the casing or bonding cement might indicate undeclared side boreholes obscured by casing.

Perhaps one of the more crucial design features of a borehole of interest for DIV is borehole orientation. That is, does the borehole follow the trajectory declared by the State? Minor deviations from intended borehole trajectories can be expected to some degree; however, major deviations might be cause for concern. Examples include, a dog-leg that turns a vertical borehole towards the horizontal.

A related possibility is the existence of a dog-leg or side-hole. Undeclared side boreholes could be used to divert waste canisters from deeper emplacement into shallower, more-readily accessible locations, potentially providing a location where disposal canisters await subsequent (undeclared) recovery (Figure 5).

Casing properties can affect ease of retrievability (Section 3.5). For example, casing made of especially strong, thick and/or corrosion-resistant steel, especially if not part of the declared design, might indicate

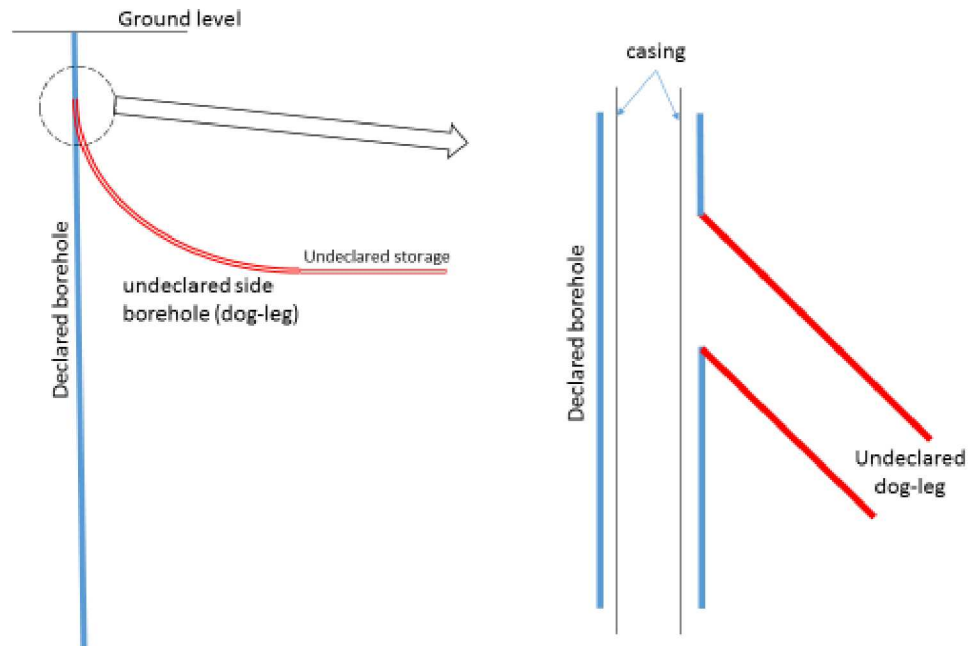


Figure 5. Schematic depiction of an undeclared side borehole (“dog leg”) that leads to a shallow undeclared storage area (left); the dog leg is obscured by borehole casing (right).

latent plans to retrieve canisters at some later time. The presence of certain down-hole lubricants might also indicate plans for retrieving waste.

Casing diameter is another potential indicator of retrieval plans, as casing with a diameter considerably larger than required for emplacing waste canisters could enhance later recovery efforts. Casing diameter that is larger than declared would therefore be a feature of potential safeguards concern (especially if combined with high-strength steel casing). To some degree, casing properties such as steel quality and diameter can be checked before these are installed downhole; however, the potential for undeclared stocks of such casing that can be installed clandestinely cannot be ignored.

The installation of casing with a greater-than-declared diameter could be concealed by 'hiding' it behind casing with the declared diameter. The outer, as-declared casing could then be removed after inspection to expose the larger-diameter casing. Therefore, the ability to detect undeclared large-diameter casing outside the inner casing would be another desirable feature for borehole tools being considered for DIV inspections.

Seals: As noted in Section 3.1.3, borehole seals that are installed during final borehole closure are of potential safeguards interest; however, the ability to inspect seals will likely be limited to examination at the surface.

5. DOWN-HOLE INSPECTION EQUIPMENT

Technologies with potential for verifying DBH design are described in this section.⁶ Borehole inspection equipment considered in this report is largely limited to that which can obtain information relevant to these key design features described in the previous Section. Such equipment includes tools for imaging boreholes (Section 5.2), for measuring borehole diameter (Section 5.3), for measuring casing properties (Section 5.4), including bonding cement (Section 5.4.2), and for surveying borehole orientation (Section 5.5). Some equipment has the capability to perform multiple functions (e.g., acoustic imaging can also determine casing/pipe diameter), and multiple tools are commonly combined so that multiple properties can be measured during a single trip downhole.

5.1. Criteria for safeguards equipment

Before describing COTS equipment, we describe criteria used to evaluate COTS borehole inspection and logging equipment for potential use in DIV inspections.

DIV inspection equipment must satisfy IAEA requirements for operational, functional, and financial considerations. The IAEA has a mandate to make independent measurements so that the Agency can draw independent and unbiased safeguards conclusions. The IAEA also has an obligation to minimize the impact of safeguards on operations at a facility or site. Furthermore, the IAEA is monitoring an increasing number of facilities and must consider tools and techniques that can meet all objectives in a cost-effective manner.

Thirteen criteria are used to evaluate COTS borehole inspection equipment for potential safeguards use. These criteria fit within five categories: deployability, operational impact, cost, confidence, and maintenance.

- Deployability
 - *Safety*: Can the equipment be installed on-site without creating new hazards?
 - *Timeliness*: Can the equipment as it currently exists be deployed, or is additional development or modification required?
 - *Resource Intensiveness*: Does the equipment require extensive site modifications in order to operate at the site? Are installation and maintenance effort and times reasonable, or do they require excessive site personnel and/or time?
- Operational Impact
 - *Footprint*: Does the space and infrastructure required to install and operate the equipment impact site operations?
 - *Operational Security*: Does the equipment capture sensitive or proprietary information that must be protected?
 - *Category*: Are data readily extracted or interrogated? Are data in a useful format for manipulation, filtering, storage?

⁶ An extensive (though not exhaustive) list of borehole-inspection tools available from a variety of manufactures was compiled last year (2016) by the Bureau of Safety and Environmental Enforcement (BSEE); it is reproduced in Appendix B.

- Cost
 - *Equipment*: Is the purchase price of new equipment reasonable? Are installation costs and other costs related to *Resource Intensiveness* reasonable?
 - *Lifecycle*: Are lifetime costs reasonable (installation, maintenance, repairs, replacement parts)? What is the expected service lifetime?
 - *Note*: Because the operating conditions of deep borehole are specialized (compared to conventional drilling operations) and equipment will require some degree of customization for the intended use, detailed cost estimates could not be obtained for this report.
- Confidence
 - *Functionality*: Does the equipment achieve verification objectives?
 - *Integrity*: Is the equipment readily accessible when needed, and is its integrity verifiable?
- Maintainability
 - *Robustness*: Can the equipment function properly in the expected operating environments, including handling, dropping, temperature and pressure extremes?
 - *Reliability*: Can the equipment operate for its expected lifetime without failing?
 - *Maintenance Minimization*: How frequently does the equipment need to be serviced or repaired? Are components reliable and long-lived? (*cf. Lifecycle Costs*)

Primary considerations include equipment operating ranges: maximum temperature (T_{\max}), depth (especially maximum pressure, P_{\max}) and borehole and/or casing diameter (D_{\max}). Ambient down-hole temperatures might be expected to range between approximately 60° and 180° C, and bottom-hole pressures will range up to approximately 55 or 60 MPa. The minimum casing diameter to be inspected is that of the guidance tieback and guidance liner from the reference design (13⁵/₈ in; Table 1), for which a 17-inch borehole is specified in the disposal zone (below 3,000 m); however, larger casings and borehole diameters are specified above 3,000 m (Table 1 and Figure 3). Another crucial capability is that an inspection tool should be able to examine the full length of a DBH, from the surface to 5 km depth, and to either store survey data in memory for subsequent retrieval and transfer to a computer at the surface, or to communicate (and transfer data) to the surface through an appropriate telemetry system⁷. Most instruments described in this report are designed to operate to about 125° C or more, and at pressures near or above 50 MPa. However, some equipment designed for shallower depths, pressures, temperatures, and (especially) borehole and/or casing diameter, have been included.⁸ These may be useful for inspecting the upper kilometer or so, or they might be modified to be operable at greater depths. Complete operating restrictions were not available for all COTS tools surveyed, and some parameters are therefore unspecified for these tools (noted as “unknown”). Table 3 further identifies key selection criteria.

⁷ Requirements for joint use of operator equipment (for inspection and/or telemetry) is not addressed in this report.

⁸ Maximum borehole and casing diameters (D_{\max}) refer to inside diameter (ID) unless otherwise noted; most are shown in inches.

Table 3. Technical Selection Criteria for Borehole Inspection Tools

Criteria	Comment
----------	---------

Detect gaps or penetrations in casing (~ borehole diameter)	Borehole imaging; Casing properties (EM or acoustic)
Detect gaps or penetrations in bonding cement (~ borehole diameter)	Casing properties (EM or acoustic)
Measure borehole diameter	Calipers (including mechanical, electronic, acoustic)
Measure borehole inclination and azimuth	Directional survey (especially inclinometers)
Operates in large diameter borehole	$D_{\max} \geq 13^{3/8}$ in (Reference diameter of inner casing, Table 1)
Operates at required depth	Up to 5 km
Operating range, maximum temperature and pressures	$T_{\max} \leq 180^{\circ} \text{C}$; $P_{\max} \leq 60 \text{ MPa}$
Data storage	Storage of logging data in memory (for later recovery) or use telemetry
Telemetry (wireless or wireline). Can communication or data be intercepted or corrupted?	Wireline preferred over wireless (may need encryption & authentication) or storage in memory for later recovery.
Inspector-operated equipment with physical chain of custody	Dedicated inspection tools kept in a secure tamper-indicating enclosure on site (TIE)
Potential joint-use equipment (data authentication & encryption)	Data encryption & authentication ⁷
Potential safety concerns with operation (special handling), including shipping & storage limitations	Hauling and hoisting required for many tools (> 15 kg); wireline use requires special training, joint-use agreement with operator, or contracting to a logging-service company.
Power requirements (supplied or battery)	Long-life battery preferred; rechargeable while in on-site storage (UPS to storage building)
Ease of data interpretation	Optical images not generally a problem, but interpreting acoustic and EM-based data and some other surveys (e.g., directional) may require special training.

5.2. Equipment for Borehole Imaging

Perhaps the most fundamental to DIV is visual inspection; that is, for an inspector to observe the facility being inspected. The challenge for visual inspection of a DBH is to provide an inspector with appropriate

tools to do so, as direct observation of a borehole is not possible. This challenge has long been answered by the drilling industry through the use of downhole viewing cameras. The most straightforward viewing device is an optical video camera, sometimes called a “fish-eye” camera because of its wide-angle lens. Such optical-imaging tools are in common use by the drilling industry to visually inspect conventional boreholes. Optical cameras include video cameras (Section 5.2.1.1) and optical televiwers (Section 5.2.1.2). These can provide intuitive images, usually with minimal or no image processing. Optical cameras can be used in air (or clear water).

In addition to optical cameras, downhole images can also be produced by ultrasonic scanners, also called acoustic televiwers (ATV) (Section 5.2.1.3). However, these require a borehole fluid to act as an acoustic-coupling medium (water, brine, drilling mud, etc.) and do not operate effectively in air. Multiple imaging methods are commonly used to complement each other and can be combined into a single inspection tool.

Optical and acoustic imaging systems are especially promising DIV inspection tools, although routine use at the depths, temperatures and pressures in the lower reaches of a deep borehole may be restricted by design limits for many COTS video cameras, OTVs and ATVs, many of which are designed for inspecting much shallower boreholes and water wells and therefore might not withstand the environmental conditions in a deep borehole. In addition, the scanning rate, or logging speed, for ATVs and OTVs is rather slow, ranging from approximately one to three meters per minute. A single survey of the entire length (5,000 m) of a completed deep borehole could therefore take several days to complete (ranging from approximately 30 to 80 hours). This might dictate DIV inspection be conducted on shorter depth intervals, otherwise a DIV inspection that uses ATV and/or OTV systems could unduly interfere with borehole operations.

A great many COTS imaging systems are designed for use in conventional boreholes and water wells (maximum temperature and pressure of 70°C and 20 MPa), considerably below temperatures and pressures expected in the lower reaches of a deep borehole: *ca.* 150-180°C and 55-60 MPa (B. W. Arnold, et al. 2011, p. 28). Nevertheless, the combined use of suitably designed (or modified) imaging systems could provide high-quality images of borehole casing characteristics of interest for DIV inspections, including breaks, seams, openings, and other features that might indicate undeclared design variations.

5.2.1.1. Optical video cameras

A wide variety of commercial borehole video cameras are available; however, a great many are designed for use in wells that are considerably shallower than a DBH, such as water wells. We list some down-hole video cameras with potential applications for DIV inspections, most of which are limited to tools that are rated for operation at depths, temperatures and pressures for a DBH (Table 4). In addition, video cameras are commonly included with other down-hole inspection equipment, notably calipers (Section 5.3) and directional survey instruments (Section 5.5.1), many of which are rated for expected DBH conditions (Table 7 and Table 11).

Table 4. Downhole Viewing Optical/Video Cameras

Manufacturer	Instrument/model	Operating Range (T_{max} , P_{max} , D_{max})	Comments
Expro ⁹	DHV ViewMAX Lite™	T_{max} unknown P_{max} unknown (rated as “high pressure”) D_{max} unknown	Side & down view single-wire conductor for power & telemetry, or fiber optic
Expro ⁹	DHV high-temperature camera	$T_{max} \leq 200^{\circ} C$ P_{max} unknown D_{max} unknown	Can deploy on conventional single or multi-conductor cable
Expro ⁹	DHV memory camera	T_{max} unknown P_{max} unknown D_{max} unknown	records up to 2,200 images in memory operate on slickline or coil tubing
Roschen ¹⁰	RS2200 Calibration Angle Electric Inclinometer Downhole Camera	T_{max} 250°C (w/ insulation protection) P_{max} unknown D_{max} unknown	Includes inclinometer for borehole orientation (Table 11)
Roschen ¹⁰	RS2500 Electric Inclinometer Downhole Camera Single Shot Instruments	T_{max} 250°C (w/ insulation protection) P_{max} unknown D_{max} unknown	Includes inclinometer for borehole orientation (Table 11)
Roschen ¹⁰	RS3000 Single Shot electronic Inclinometer and Downhole Camera with LCD display	T_{max} 250°C (w/ insulation protection) P_{max} unknown D_{max} unknown	Single Shot; Includes inclinometer for borehole orientation (Table 11)
Roschen ¹⁰	RS5000	T_{max} 250°C (w/ insulation	Can also operate as a single shot;

⁹ Expro web site: <http://exprogroup.com/>

¹⁰ Roschen web site: www.explorationcoredrilling.com

Manufacturer	Instrument/model	Operating Range (T_{max} , P_{max} , D_{max})	Comments
	Multi Shot Electronic Inclinometer		

		protection)	
		P_{max} unknown	Includes inclinometer for borehole orientation (Table 11)
		D_{max} unknown	
Roschen¹⁰	RS-10 Core Orientation Downhole Camera for Down Hole Survey Instruments	T_{max} 175°C (w/ heat shield) P_{max} 140 MPa D_{max} unknown	Includes inclinometer for borehole orientation (Table 11)

5.2.1.2. Optical Televiewers (OTV)

More specialized than down-hole video cameras described above are optical televiewers (OTV). These imaging systems use a ring of lights to illuminate the entire circumference of a borehole, and a reflector focuses a 360° slice of the borehole wall into the camera lens (Figure 6). Like optical video cameras, OTV systems operate only in air- or clear-water-filled borehole intervals, not in opaque media such as drilling mud. Conditions that affect the clarity of borehole water or produce coatings on borehole or casing walls will negatively impact the quality of OTV images (unflushed drilling mud, chemical precipitation, bacterial growth, etc.). Nevertheless, acceptable OTV images can be obtained in borehole intervals where conventional fish-eye camera images may be poor as a result of cloudy water. This is because the focal length for a side-looking OTV is shorter than that of a down-looking fish-eye camera.

The optical image scan is either sent up the logging cable as an analog signal and digitized uphole or digitized downhole and sent up as a digital signal. The maximum borehole diameter in which conventional OTV images can be collected are typically 0.3 m or less. Typical logging speeds for OTV systems are on the order of one meter per minute (1 m/min). Downhole-digitized systems require slower logging speeds than uphole-digital systems, but downhole-digitized systems can be used on greater lengths of cable and on a wider range of cable types, including single conductor. The fastest logging speeds (3 m/min) are generally attained by a system that simultaneously transmits multiple scanned slices of the borehole wall uphole as an analog signal on coaxial cable (Williams & Johnson, 2004). Most available OTV systems examined for this report are designed for inspecting water and exploration wells



Figure 6. Example of an OTV system with down-looking fish-eye camera (at left) and side-view camera for OTV (near center of image).

considerably shallower than a DBH, with maximum pressures on the order of 10 to 20 MPa, maximum temperatures of 60° to 70° C, and operating depths less than about 2,000 m; however, detailed operating

conditions are not available for all OTVs reviewed (Table 5). Despite this potential shortcoming, the advantages of using OTVs to obtain detailed, high-resolution optical images of a borehole and casing suggest these tools show considerable promise as DIV inspection tools, at least for the upper reaches of a borehole, and some may be modifiable to operate at greater depths.

Table 5. Optical Televiewer (OTV) Systems

Manufacturer	Instrument/model	Operating Range (T_{max} , P_{max} , D_{max})	Comments
Robertson Geologging ¹¹	Hi-Resolution Optical Televiewer (Hi-OPTV)	T_{max} 60° C P_{max} 20 MPa D_{max} unknown	Fish-eye lens
GeoVista ¹²	Optical Televiewer	T_{max} 50° C P_{max} 15 MPa (extended option) D_{max} unknown	2,000-ft maximum depth (wireline); CMOS image sensor 5 kg
ALT (Advanced Logic Technology) ¹³	Optical Borehole Imager QL400BI-2G	T_{max} 70° C P_{max} 20 MPa D_{max} 21 in	CMOS image sensor 5.3 kg Also available through Mount Sopris Instruments ¹⁴
Weatherford ¹⁵	Slimline optical televiewer (OTV)	T_{max} unknown P_{max} unknown D_{max} unknown	CCD camera
Direct Systems ¹⁶	Optical Borehole Televiewer	T_{max} unknown P_{max} unknown D_{max} unknown	

¹¹ Robertson Geologging web site: www.geologging.com

¹² GeoVista web site: <http://geovista.co.uk>

¹³ ALT website: www.alt.lu

¹⁴ Mount Sopris Instruments web site: <http://mountsopris.com>

¹⁵ Weatherford web site: www.weatherford.com

¹⁶ Direct Systems web site: www.directsystems.org

5.2.1.3. Acoustic Televiewers (ATV)

ATV imaging systems use an ultrasonic pulse-echo transducer to generate an acoustic wave that is both reflected and refracted by the casing and borehole wall (Figure 7). Transit time and amplitude of the reflected acoustic signal are recorded as photographic-like images of the surface of the casing and/or borehole wall; transit-time data can also be used to generate high-resolution caliper logs of borehole diameter (see Section 5.3). Most modern ATV systems digitize the analog signal downhole and send the digitized image uphole for display and analysis on a computer.

In a conventional ATV system, the transducer is rotated on a motor-driven shaft while the tool is pulled uphole. In a fixed transducer system, the acoustic beam is bounced off a rotating convex reflector. Fixed high-frequency transducer systems have vertical resolutions of 1 to 2 mm and can be used in boreholes as large as 0.4 m in diameter, adequate for the guidance tieback in the reference borehole design, although smaller than the intermediate casing in the reference design (Table 1). Logging speeds for collecting ATV images range from 1 to 3 m/min.

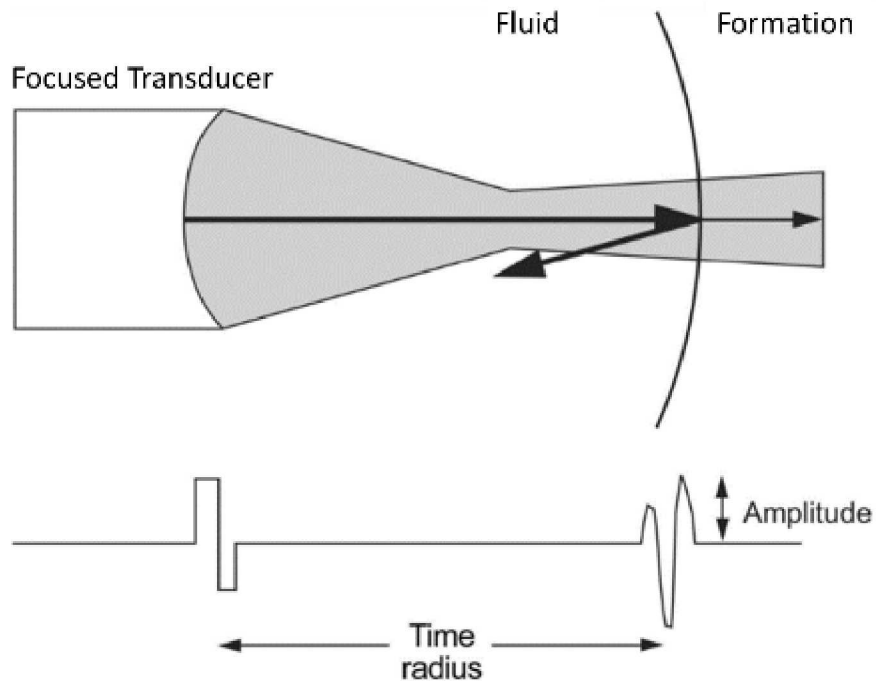


Figure 7. Illustration of the principle of an ultrasonic acoustic borehole imager, which measures reflection amplitude and radial distance by using a direct measurement of the fluid velocity. Long arrow point to the right represents the transducer signal; the two smaller arrows represent the reflected and refracted signals (pointing left and right, respectively).

ATV images require a sound-coupling fluid, such as water- or mud-filled borehole intervals and so cannot perform well in air-filled boreholes. Multi-echo ATV systems record the full wave train of a reflected acoustic signal and can obtain images from behind some light casing materials, which could be useful for

detecting undeclared features, such as dog legs or side holes, hidden behind casing or other obstructions. Obtaining reliable images for such features behind steel casing, however, is generally performed by other means (see Section 5.4.2). We list some ATV manufacturers of tools with potential application for DIV inspections of a DBH (Table 6).

Table 6. Acoustic Televierer (ATV) Systems

Manufacturer	Instrument/model	Operating Range (T_{max} , P_{max} , D_{max})	Comments
Halliburton ¹⁷	CAST series	T_{max} 175 °C P_{max} 138 MPa D_{max} 20 in	
Southwest Exploration Services, LLC ¹⁸	ABI-43 Full Waveform Acoustic Televierer	T_{max} 135 °C P_{max} 80 MPa D_{max} >15¾ in (tested in 17½ in)	tested to 2,400 m depth
Schlumberger ¹⁹	UBI Ultrasonic Borehole Imager	T_{max} unknown P_{max} unknown D_{max} unknown	
Schlumberger ¹⁹	USI Ultrasonic Imager Tool	T_{max} 177 °C P_{max} 138 MPa D_{max} 13¾ in	
Weatherford ¹⁵	Ultrasonic Radial Scanner (URS)	T_{max} 177 °C P_{max} 138 MPa D_{max} 13¾ in	Maximum depth (run length) 1,400 m
Direct Systems ¹⁶	Acoustic Borehole Televierer	T_{max} 70° C P_{max} 20 MPa D_{max} unknown	Low P & T

¹⁷ Halliburton web site: www.halliburton.com

¹⁸ Southwest Exploration Services web site: <https://swexp.com/>

¹⁹ Schlumberger web site: www.slb.com

5.3. Borehole Diameter

As noted in Section 4, casing diameter is a declared design parameter, and deviations from that diameter might indicate a potential for undeclared use. In particular, larger-than-specified casing diameter could facilitate subsequent retrieval of emplaced waste canisters. Casing diameter is therefore a parameter of potential interest for DIV inspections. As noted above, some ATVs and other acoustic-based tools can be used to inspect casing diameter (Sections 5.2.1.3 and 5.4.2); however, such tools require a fluid be present and do not operate in air. Physical calipers are therefore used to measure casing diameter in air-filled boreholes. These are described in the following Section.

5.3.1. Cased-hole calipers

Physical calipers are among the most common tools used to measure casing diameter. The oil and gas industry commonly uses them to identify casing wear and corrosion, and these tools can be quite sensitive to small changes. Many calipers also include inclinometers, so that many caliper tools can also be used to determine if a borehole deviates from vertical (See Section 5.5.1, Directional Survey Instruments).

Multi-finger calipers (MFC), the most common type of cased-hole caliper, can have up to 80 spring-loaded “fingers” (or “arms”), depending on the casing diameter to be inspected. These fingers extend in wider sections (e.g., a pit, hole or gap) and retract where diameter decreases. Commercially available MFCs can measure internal casing diameter with a radial resolution of a few thousandths of an inch (~0.1 mm) and a vertical resolution of a few hundredths of an inch (~1 mm) at a typical logging speed of approximately 10 m/min. This is beyond the precision likely to be required for most DIV inspections (which might, therefore, be able to employ faster logging speeds). MFC data can be used to produce a three-dimensional image of the casing. Data is either transmitted to the surface on a wireline or stored downhole in the tool’s memory if the tool is deployed on a slick line.

Multi-finger calipers can be categorized as either mechanical or electronic, although the distinction is somewhat misleading, as all MFCs are deployed mechanically. The distinguishing difference is in the way in which data are recorded. Older MFCs were truly mechanical in that they were operated on a slick line and used a scribe chart for recording downhole data. Such calipers are rated for high temperature because they are not limited by downhole electronics (e.g., 315°C for the Kinley caliper from Expro Group; Table 7). By contrast, electronic MFCs convert mechanical data into electronic information for storing in memory downhole or for transmitting uphole for real-time data display. Operating temperatures for these electronic tools are typically up to 177°C, still in the range expected for a DBH at depth. Some borehole caliper tools for possible use as DIV inspection tools for DBH are listed in Table 7. Acoustic-based calipers are described separately in Section 5.4, as these are used to investigate casing properties in addition to diameter.

Table 7. Cased-hole Caliper Tools

Manufacturer	Instrument/model	Operating Range (T_{max} , P_{max} , D_{max})	Comments
Expro⁹	Mega Data Caliper (w/ DigiCal digitization software)	T_{max} 315°C P_{max} “unlimited” D_{max} 16 in	Data stored in memory.
Expro⁹	Kinley Caliper (w/ DigiCal digitization software)	T_{max} 315°C P_{max} 138 MPa D_{max} 13 ⁵ / ₈ in	Data stored in memory Tested to 9,000 m depth
Spartek Systems²⁰	Multi-finger caliper (MFC)	T_{max} 175°C P_{max} 103 MPa D_{max} 9.63 in	7.3 to 31 kg
Hotwell²¹	Multi-finger caliper (MFC)	T_{max} 175°C P_{max} 103 MPa D_{max} unknown	7.3 to 31 kg
Probe²²	MAC Multi-arm caliper tools	T_{max} 177°C P_{max} 103 MPa D_{max} 13.4 in (extended model)	Includes inclination; 8.5 to 61 kg
Gowell²³	Multi-finger Caliper (MFC56C-C)	T_{max} 177°C P_{max} 100 MPa D_{max} 13 ⁷ / ₈ in (extended arms option)	63 kg

²⁰ Spartek Systems web site: <http://sparteksystems.com>

²¹ Hotwell web site: <http://www.hotwell.at>

²² Probe web site: www.probe1.com

²³ Gowell web site: www.gowellpetro.com

5.4. Casing Properties

The oil and gas industry inspects casing properties to monitor potential deterioration of casing integrity, which may arise from corrosion or deformation. From a DIV perspective, casing properties of safeguards interest can include casing thickness and potential gaps, as well as properties related to casing material and strength (e.g., a stainless-steel casing where mild (carbon) steel is indicated). Such casing properties can be examined by using ultrasonic, magnetic, and electromagnetic methods, as well as with many physical calipers described in the previous section (Section 5.3). In this section we describe flux-leakage tools (5.4.1) and ultrasonic tools (5.4.2).

5.4.1. Magnetic Flux Leakage tools

Magnetic flux leakage (MFL) is a semi-quantitative method that uses a strong magnetic field to identify thinning or pitting of the casing, commonly caused by corrosion. A downhole electromagnet that fits snugly within the casing creates a low-frequency or a direct-current magnetic field. Magnetic flux is concentrated within the casing, which is close to magnetic saturation. Where thinning or pitting of the casing is encountered, lines of flux "bulge out" from the casing as though they were leaking from it. Sensors passing through this leaking flux measure the induced voltage. The amplitude and spatial extent of the sensor response is related to the volume and shape of the corrosion metal loss, thereby allowing an estimate of a defect's size. Because the primary measurement cannot distinguish between internal and external casing defects, many tools use an additional higher-frequency eddy-current, which uses a separate transmitter coil. The higher-frequency eddy current is sensitive to casing defects on the inner wall only. The flux-leakage and eddy-current signals are distinguished by using frequency filters. These dual-frequency electromagnetic (EM) MFL tools are also called magnetic thickness tools (MTT) because of their sensitivity to casing thickness.

MFL tools can identify localized casing defects as small as about 5 mm, well beyond the precision of likely interest for DIV inspections. MFL is also affected by changes in the electromagnetic properties of casing; for example, a change from mild (carbon) steel to stainless steel will be detectable through a change in the tool's coil-sensor response. However, the coil-sensor response can be sensitive to logging speed, making quantitative interpretation difficult.

The use of MFL tools for DIV inspections is considered most applicable to locating large-scale defects, such as gaps or missing pipe sections, as well as changes in casing properties that might indicate a change in casing material. Gaps and missing sections might indicate deviations from the declared design, including potential side holes or dog legs. Changes in material properties might reflect a change in casing properties that might also indicate undeclared design changes, such as installation of high-strength or corrosion-resistant casing that could facilitate later retrieval of waste canisters.²⁴ Potentially promising DIV-applicable MFL tools examined for this report are listed in Table 8.

²⁴ Note that a mixture of stainless and carbon steels, combined with the special magnetic properties of stainless steel, can create a challenging environment for inline inspection tools that use magnetic flux leakage (MFL) technology ().

Table 8. Magnetic Flux Leakage Tools for Inspecting Borehole Casing

Manufacturer	Instrument/model	Operating Range (T_{max} , P_{max} , D_{max})	Comments
Gowell²³	Magnetic Thickness Detector (MTD43C-E)	T_{max} 177°C P_{max} 100 MPa D_{max} 18 ⁵ / ₈ in	Includes 3-axis accelerometer for measuring inclination; 3-pipe capability 5 kg
Hotwell²¹	Omni Directional Thickness (ODT)	T_{max} 175°C P_{max} 103 MPa D_{max} 10 in	15 kg
Spartek Systems²⁰	Casing Inspection Tool (MFL-800)	T_{max} 150°C P_{max} 103 MPa D_{max} 12 ³ / ₄ in	160 kg
Halliburton¹⁷	Magnetic Thickness Tool (MTT)	T_{max} unknown P_{max} unknown D_{max} unknown	Tool specifications unavailable
Halliburton¹⁷	Xaminer Electromagnetic Corrosion Tool	T_{max} 150°C P_{max} 100 MPa D_{max} 18 ⁵ / ₈ in	dual-frequency EM
Schlumberger¹⁹	EM Pipe Scanner	T_{max} 150°C P_{max} 103 MPa D_{max} 9 ⁵ / ₈ in	dual -frequency EM
Hotwell²¹	EM Defectoscope (EMDS)	T_{max} 175°C P_{max} 100 MPa D_{max} 12.75 in	dual -frequency EM
TGT²⁵	Magnetic Imaging Defectoscope MID-2M	T_{max} 125°C P_{max} 100 MPa D_{max} 14 in	dual -frequency EM

²⁵ TGT web site: www.tgtoil.com

5.4.2. Ultrasonic casing and cement-evaluation tools

The ultrasonic method can provide a quantitative record of casing radius and thickness. As described in Section 5.2.1.3, ATVs are effective for obtaining images of the inner casing surface and some can be used to measure casing diameter. Acoustic inspection tools with fixed ultrasonic transducers are used primarily for cement evaluation but also provide information about casing thickness. The ability to combine imaging with cement-bond evaluation is possible by using a rotating ultrasonic transducer. Like ATVs (and other acoustically based tools), ultrasonic cement-evaluation tools require an acoustic coupling medium such as water or mud. They cannot operate effectively in air.

An acoustic cement-bond log (CBL) records acoustic coupling between cement and borehole casing and between cement and borehole wall. These tools operate on the principle that acoustic amplitude is rapidly attenuated in a strongly adhering cement bond but not in partial bond or a free pipe; i.e., a pipe with no cement bonded to it.

Most acoustic cement-evaluation (cement-bond) tools consist of one or more axially symmetric monopole transmitters and one or more receivers. When an acoustic wave generated by a tool's transmitter reaches the casing, part is refracted down the casing and part travels through the mud; other parts are refracted into the annulus and the formation at the borehole wall. The arrival times of these signals at the receiver comprise the data that make up a CBL. Tool response depends on the acoustic impedance of the cement, which, in turn is a function of density and velocity. CBLs can vary over time as the cement cures and its properties change. Many conventional CBL tools provide measurements averaged over the casing's circumference, whereas many newer radial cement-evaluation tools provide azimuthally sensitive measurements.

From the perspective of information of interest to a DIV inspection, being able to detect a section of missing cement (a gap) could indicate a potential side hole or dog leg hidden behind the borehole casing. This would seem a straightforward application of an acoustic CBL tool, and well within the capabilities of current instruments. The need to perform acoustic measurements within a coupling medium, such as mud or water, would obviate this method's applicability in air-filled boreholes. Potentially promising DIV-applicable MFL tools examined for this report are listed in Table 9.

Table 9. Ultrasonic Tools for Evaluating Casing and Cement

Manufacturer	Instrument/model	Operating Range (T_{max} , P_{max} , D_{max})	Comments
Halliburton ¹⁷	Circumferential Acoustic Scanning Tool – Extended Range (CAST-XR)	T_{max} 175°C P_{max} 140 MPa D_{max} 20 in	Borehole diameter <i>Cf.</i> Table 6
Halliburton ¹⁷	Xaminer Sonic Imager (XSI)	T_{max} 177°C P_{max} 138 MPa D_{max} 20 – 22 in	

Halliburton¹⁷	Borehole Sonic Array Tool (BSAT)	T_{max} 177°C P_{max} 138 MPa D_{max} 20 – 22 in	Cement-evaluation option 144 kg
Schlumberger¹⁹	Ultrasonic Corrosion Imager (UCI™)	T _{max} 177°C P _{max} 138 MPa D _{max} 13 ³ / ₈ in	
Schlumberger¹⁹	Sonic Scanner	T _{max} 177 °C P _{max} 138 MPa D _{max} 22 in	
Baker-Hughes²⁶	Acoustic Cement Bond Log	T _{max} 177°C P _{max} 138 MPa D _{max} 9.62 in	

By combining tools with complementary measurement capabilities, a more complete evaluation of relevant properties of borehole casing and cement can be obtained. Some tools operate in air, others require a fluid be present. In addition, different tools are more or less sensitive to specific properties. Table 10 lists a some tools that provide a wide range of measurements in different media (fluid vs. air) to illustrate their potential complementarity for DIV use. The choice of any particular combination will depend on objectives, borehole conditions, and other considerations.

²⁶ Baker-Hughes web site: www.bakerhughes.com

Table 10. Complementary Tools for Measuring Casing & Cement Properties

Application	CAST*	MFC*	MFL*	Xaminer ECT*
Multiple Barrier Inspection	No	No	No	Yes
Measure Average Thickness of Casing/Tubular	Yes	No	Yes	Yes
Measure Radial Thickness	Yes	No	Yes	No
Measure Circumferential Radii	Yes	Yes	No	No
Identify Holes, Gaps or Breaks	Yes	Yes	Yes	No
Operate in Air	No	Yes	Yes	Yes

* CAST: Circumferential Acoustic Scanning Tool (Halliburton trademark); MFC: Multi-finger caliper; MFL: Magnetic flux leakage, example shown applies to Halliburton’s MTT (magnetic thickness tool); ECT: Electromagnetic Corrosion Tool (“Xaminer ECT” made by Halliburton).

5.5. Directional Surveys

Based on the reference design, deviation of the borehole from its designed trajectory must be controlled such that the distance between any two boreholes is not greater than 50 m at a bottom depth of 5,000 m (B. W. Arnold, et al. 2011, p. 20). This implies an average deviation in the hole trajectory of less than 0.6°, which will necessitate directional drilling to control or correct any borehole deviation. Thus, the drilling operator will require directional-drilling capabilities, as well as tools for measuring borehole deviation. The potential for undeclared deviations from (a vertical) design or undeclared side boreholes (dog legs) is therefore a concern for safeguards DIV, and DIV inspections will require the capability to conduct directional surveys that can verify declared borehole trajectory.

Directional surveying is used to measure, calculate and plot the path of a borehole in three dimensions. Relevant parameters are measured at multiple locations along the borehole path; these include measured depth (MD), inclination, and hole direction (azimuth). Directional surveys are conducted for one of two primary reasons: (1) to direct and define the trajectory of the borehole during the drilling process (“geosteering”) and (2) to characterize the borehole path after drilling. The drilling operator is interested in the former; whereas, the latter is of primary interest in the context of DIV inspections for deep boreholes.

In directional-survey terminology, *azimuth* is the orientation of the borehole relative to "north," which may be defined as magnetic north, geographic north, or grid north (with reference to a specified geographic coordinate system). *Inclination* is the deviation of a borehole from vertical. Azimuth and inclination define the trajectory of a borehole along its length, usually relative to the location of the wellhead (at the surface). *Tool face* refers to the angle between a reference direction on a downhole tool and a fixed reference in space; that is, it quantifies the direction in which the measurement tool is pointing.

There are two types of directional surveys: *magnetic* and *gyroscopic*. They can be run by using either single- or multi-shot tools that can be powered from the surface or with downhole batteries. It is likely that a single-shot tool will suffice for the primary purpose of a DIV inspection (that is, to verify – or not – that the borehole has been drilled as declared); however, a multi-shot tool can provide a more accurate determination of borehole configuration and could be required if a borehole configuration needs more complete characterization.

Magnetic surveys can be run on the drill string while tripping or on a wireline (conducting cable) after drilling, the latter approach being most relevant to DIV inspections. Magnetic surveys are generally conducted in uncased, open boreholes, due to magnetic interference from the steel. A simple magnetic-survey tool comprises a downhole inclinometer and a compass; however, more advanced tools include arrays of three-axis accelerometers (inclinometers) and magnetometers. A three-axis accelerometer measures three orthogonal components of gravity, which combine to give the direction of Earth's gravitational field relative to the axis of the tool and a reference position on the tool's circumference. By combining accelerometer and magnetometer data, it is possible to calculate the inclination, I , and azimuth, A , of the tool. By correcting for the "tool face," the inclination, α , and azimuth, β , of the borehole can be determined (Figure 8).

Magnetic measurements are impacted by short-term variations in Earth's magnetic field and by their proximity to magnetic materials such as drill pipe and casing, and to magnetic minerals in adjacent rock (or in the drilling mud). These problems can be mitigated through the use of nonmagnetic drill collars and repeat measurements with different alignments of the tool in the borehole. But even where magnetic-survey tools are run in long lengths of nonmagnetic drill collars, there can still be a significant effect from steel drill-string tools (see Appendix C for a discussion of survey errors).

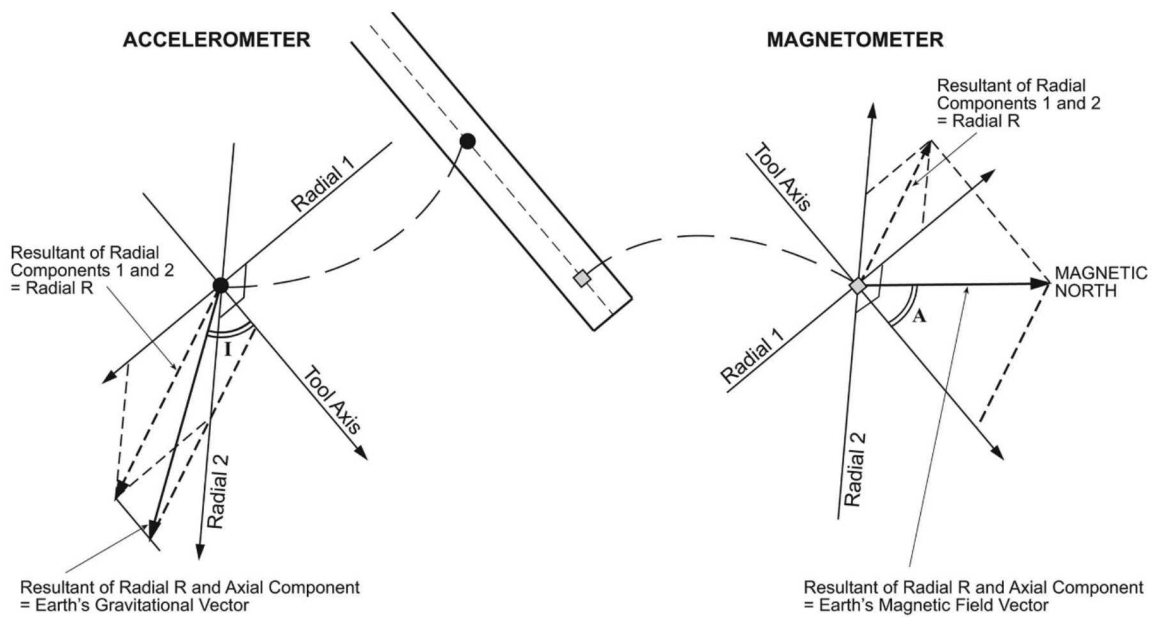


Figure 8. Graphical illustration of a three-axis magnetometer and data used to calculate inclination and azimuth of the survey tool and the borehole.

Gyroscopic surveying instruments are used when the accuracy of a magnetic survey system may be corrupted by extraneous influences, such as cased holes, production tubing, geographic location, or nearby wells. A rotor gyroscope consists of a spinning wheel mounted on a shaft, commonly powered by

an electric motor that can reach speeds over 40,000 rev/min (although most commonly mechanically driven, methods that use a rotating beam of light have been developed by using fiber optics and laser technology). The spinning rotor can be oriented in a known direction. The direction in which the gyro spin is maintained by inertia can therefore be used to measure azimuth. Outer and inner gimbal stabilizers allow the gyroscope to maintain its preset direction, regardless of how the instrument is positioned in the borehole. Mechanical gyroscopes are characterized according to their freedom of movement and number of flywheels (one to three). Three-axis systems are superior in highly deviated and horizontal wells. Three categories of gyroscopic systems (gyros) are in use: Free gyros, Rate gyros, and Inertial navigation systems.

Free gyros comprise three types: tilt scale, level rotor, and stable platform. Most free gyros in use today are stable-platform gyros because they have shorter run times and faster data processing compared with the other two types; they also monitor continuously. Free gyros use a two-gimbal gyro system (like a level-rotor gyro) which keeps the gimbals perpendicular to each other – even when the instrument is tilted during use. The inner gimbal remains perpendicular to the tool axis (platform) instead of perpendicular to the horizon.

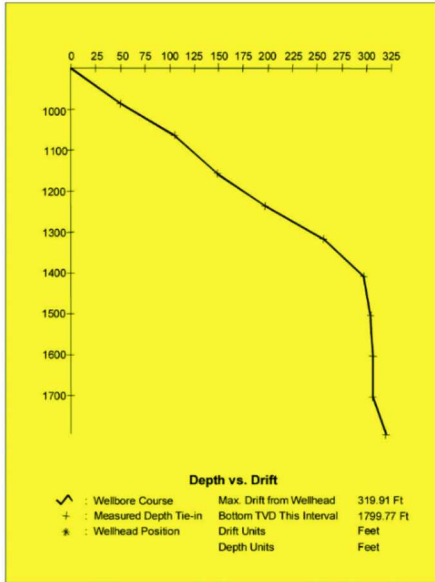
Rate gyros (north-seeking gyros) use the horizontal component of Earth's rotation to determine North. Earth rotates 360° every 24 hours (15° per hour), so that rate gyros do not rely on a known reference direction for orientation. Inclination is measured by a triaxial gravity accelerometer. Rate gyros exhibit a precise drift rate that is small compared to Earth's rotation rate, which decreases at higher latitudes. Thus, a rate gyro's ability to orient North decreases with increasing latitude. This increases the time required to seek North accurately while decreasing the accuracy of the North reference. Nevertheless, a true-north reference can generally be resolved for latitudes below about 80° North or South (Forsmark, Sweden, and Okiluoto, Finland, for example, are both located close to 60° N latitude).

Inertial navigation systems are generally considered to be the most accurate gyroscopic-survey method. Inertial navigation systems use groups of gyros to orient the system North. These instruments measure movements in the x , y , and z axes of the borehole by combining gyros and gravity accelerometers. This instrument can survey in all latitudes without sacrificing accuracy. They also tend to be the most expensive.

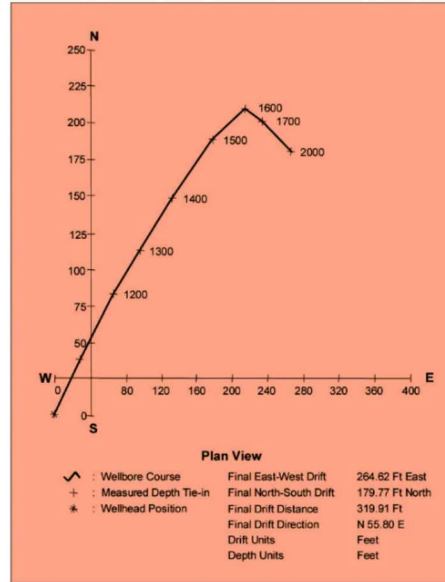
One problem with gyroscope surveys is that instrumentation is sensitive to downhole vibrations and stresses and must be run on wireline. Because gyroscopic surveys interrupt drilling, their use as a DIV tool would likely be limited to surveys after completion (or possibly during breaks between drilling activities). However, unlike magnetometers (above), gyros can be run in a cased hole, and should therefore be suitable for DIV inspections conducted after borehole completion.

Results of a directional surveying usually take the form of inclination, α , and azimuth, β , of a borehole at a sequence of survey stations and can be plotted on a well-path plot and plan (map) view (Figure 9). Although this information does not fully describe the shape of the borehole path or trajectory, for the purposes of DIV inspection, it is likely sufficient to identify potential deviations from declared design. Nevertheless, there are well-established methods for precisely determining a borehole's path by using data from a directional survey (Walstrom, Brown and Harvey 1969, Wolff and de Wardt 1981).

Well Path Plot



Plan View



Tabular Listing

COMPANY WELL				PAGE 1			
DEPTH	DEVIATION		TVD	DRIFT COORDINATES			TOTAL
	ANGLE	AZIMUTH		STATION	N-S	E-W	
1000.00	9.0	35.0	900.00	0.00N	0.00E	0.00N	0.00E
1100.00	50.0	37.0	985.19	38.66N	28.78E	38.66N	28.78E
1200.00	20.0	45.0	1066.17	43.70N	35.99E	82.37N	64.76E
1300.00	30.0	44.0	1156.69	30.15N	29.53E	112.52N	94.30E
1400.00	30.0	47.0	1243.29	35.04N	35.65E	147.55N	129.95E
1500.00	45.0	50.0	1322.40	40.01N	45.63E	187.56N	175.58E
1600.00	10.0	110.0	1409.73	20.63N	36.81E	208.19N	212.39E
1700.00	10.0	120.0	1508.21	7.31S	15.68E	200.88N	228.06E
1800.00	0.0	120.0	1607.70	4.35S	7.54E	196.53N	235.60E
1900.00	0.0	120.0	1707.70	0.00N	0.00E	196.53N	235.60E
2000.00	40.0	120.0	1799.78	16.76S	29.02E	179.77N	264.63E
THE FIRST POINT INFORMATION:							
1000.00	9.0	35.0	900.00	0.00N	0.00E	0.00N	0.00E
THE LAST POINT INFORMATION:							
2000.00	40.0	120.0	1799.78	16.76S	29.02E	179.77N	264.63E
FINAL EAST-WEST DRIFT				=	264.63 E		
FINAL NORTH-SOUTH DRIFT				=	179.77 N		
FINAL DRIFT DISTANCE				=	319.91 FT		
FINAL DRIFT DIRECTION				=	N 55.81 E		

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Figure 9. Example of reporting format from a directional survey (depths in feet). Vertical scale on the Well Path Plot (upper left) is true vertical depth (TVD). Depth markers on the trace in the Plan View (upper right) are measured depth (MD). The Tabular Listing links the two depth scales at measurement stations and includes borehole deviation, azimuth, and coordinates at the points of measurement.

5.5.1. Directional survey instruments

Directional-survey instruments are available from numerous manufacturers, many of which provide several models with various capabilities. Table 11 below lists some manufacturers and models that show promise as potential DIV inspection tools for surveying the orientation of deep boreholes. Detailed product descriptions are available from company web sites; specialized or customized configurations (e.g., heat shields or high-pressure modifications) may be available and have been noted where offered.

In addition to tool manufacturers, numerous companies provide directional-survey services, including Schlumberger, Halliburton, and Baker Hughes.

Table 11. Directional Survey Instruments for Boreholes

Manufacturer	Instrument/model	Operating Range (T_{max} , P_{max} , D_{max})	Comments
Roschen¹⁰	See Table 4		
Pajari Instruments LTD²⁷	Tropari SDP	T_{max} 160°C P_{max} unknown D_{max} unknown	single-shot; MEMS; Borehole direction from Earth's magnetic field (inclination only for cased holes); 90 grams
GyroMax²⁸	TwinGyro	T_{max} 80°C (optional heat shield available) P_{max} unknown D_{max} unknown	Operates in magnetic environments; 100 hr battery life; Bluetooth telemetry
GyroMax²⁸	SlimGyro	T_{max} 70°C (optional heat shield available) P_{max} unknown D_{max} unknown	Operates in magnetic environments;
GyroMax²⁸	isGyro	T_{max} 70°C (optional heat shield available) P_{max} unknown D_{max} unknown	Operates in magnetic environments; bluetooth data communication

²⁷ Pajari Instruments Ltd web site, <http://www.pajari.com/index.html>

²⁸ GyroMax website: www.gyromax.com.au

GyroMax²⁸

NorthFinder

T_{\max} 70°C (optional
heat shield
available)

Operates in magnetic
environments

P_{\max} unknown

D_{\max} unknown

6. POTENTIAL MODIFICATIONS OF COTS BOREHOLE INSPECTION TOOLS FOR DIV INSPECTIONS

Design ratings for equipment operating conditions was a primary consideration when evaluating the potential applicability of borehole-inspection tools for DIV use. Many COTS borehole-inspection tools can be used for DIV inspections, but will require testing of their capabilities under conditions relevant to a deep borehole for waste disposal: 5 km operating depth, operating temperatures up to 125°C, operating pressures up to 55 MPa, casing diameter greater than 13³/₈ in (340 mm), and functionality in air vs. drilling mud or other fluid. Most equipment evaluated for this report should require no special modifications for use in inspecting deep boreholes; however, some promising instruments with design limitations that could prevent their use at depths approaching 5 km may need modifications to their designs (or electronic components) or special add-on equipment (e.g., temperature shielding or high-pressure fixtures). In addition, we have included COTS tools for which operating parameters could not be fully ascertained. Furthermore, some tools that cannot be modified for use at depth may still be useful for inspecting upper 1,000 or 2,000 m of a borehole.

Of special note are optical and acoustic imaging systems. Most such systems that we evaluated are designed for operating at depths well above 5 km, commonly less than 2,000 m, and at temperatures and pressures well below those expected at the bottom of a DBH (70°C and 20 MPa are common temperature and pressure limits for many downhole optical viewing cameras). Nevertheless, because these imaging systems seem especially promising as DIV inspection tools, they are included in our evaluation with the caveat that they may need appropriate modifications for operation at greater depths. The details of specific modifications required and what is possible requires consultation with the tool manufacturer.

Another limiting factor for some tools is the maximum diameter pipe (casing) in which they are designed to operate. The large casing diameters used in the reference-design borehole are atypical for many common boreholes. The smallest casing diameter for the reference design is 13³/₈ in (340 mm), which appears to be near the upper limit for many tools that measure casing diameter; however, a DBH for disposal will contain considerably larger-diameter casing as well, plus larger-diameter boreholes within which that casing will be placed (Table 1). It is unclear the degree to which COTS tools with operational limits on maximum casing or borehole diameter below those needed for DIV inspections might be modified for larger-diameter applications. Multi-finger calipers may be amenable to slight modification by increasing finger length; however, tool manufacturers would need to be consulted on such possibilities. Given increasingly common large-diameter boreholes, it is also possible that some tool manufacturers have specialized tools available, but which were not discovered during our evaluation.

Finally, the operational environment of a tool is crucial to its intended use; that is, does the tool operate in air or drilling mud or both? Many COTS borehole tools with capabilities to routinely investigate casing properties and, especially, identify gaps behind casing (cement-bond logging tools in particular), must operate in a fluid-filled borehole. These include acoustic and EM scanners, which cannot be readily modified to operate in air. It is not clear whether DIV inspections would be performed only in completed air-filled boreholes, and the possibility of using these tools for their unique capabilities should remain a consideration.

7. TESTING COTS BOREHOLE INSPECTION TOOLS FOR SAFEGUARDS USE

As noted above, a great many COTS borehole-inspection tools can be used for DIV inspections, but will require testing of their capabilities under conditions relevant to a deep borehole for waste disposal. Special considerations for testing include, not only environment (depth, temperature, pressure, air or fluid), but the ability of certain tools to glean information relevant to DIV that may not be quite what some tools are designed to acquire. Of particular note is the ability to detect undeclared gaps or missing cement behind installed casing, potentially indicative of a side borehole, and the ability to identify undeclared casing behind an inner removable casing string, potentially indicative of undeclared retrieval plans.

In addition to testing and quantifying a tool's design capabilities against DIV needs, data management will also be an important consideration. This includes testing telemetry of data streams from downhole equipment to a computer at the surface against tools that store data in memory for later retrieval at the surface. Testing the uploading and interpretation of data from inspection tools will also need to be conducted before deployment in the field for DIV use.

Testing may be required before deciding whether to use single-shot tools or multi-shot tools for gathering inspection information from a survey sufficient to draw a firm safeguards conclusion about the borehole in question. Not all equipment evaluated for this report can be used in either application, so this distinction will also influence what tools are deemed most appropriate for DIV inspections.

Developing routine handling procedures will require experiential testing of equipment and equipment strings under field conditions. Given the sizes and weights of many COTS tools, proper tool handling will be a major consideration for the size and capabilities of a borehole inspection team. Deploying tools and tool strings on wireline will also require appropriate testing and training. Joint use of a drilling operator's hoisting and hauling equipment may reduce some burdens on inspectors; however, coordination will be necessary. Joint use of wireline, especially if telemetry is to be shared, would likely require data splitting, encryption and/or authentication and may need additional testing.

8. CONCLUSIONS AND RECOMMENDATIONS

A large variety of COTS borehole inspection and logging tools are available, and their use is both extensive and routine in the field. Many commercial uses for these tools can be applied directly to achieving safeguards-relevant DIV objectives. These objectives include inspecting casing and cement properties, borehole and casing diameters, and borehole trajectory. Other applications relevant to DIV inspections may require specialized modifications of certain tools. Borehole-inspection instruments to be used for DIV inspections will also require testing of their capabilities under appropriate environmental and operating conditions.

Recent progress in directional drilling makes borehole trajectory of special concern for DIV, as directional drilling of a deviated borehole could facilitate subsequent (undeclared) retrieval of waste canisters from an undeclared location. DIV inspections will therefore require the capability to conduct directional surveys that can verify borehole trajectory. In addition, being able to detect a section of missing cement (a gap) will be another objective of DIV inspections, as this could indicate a potential side hole or dog leg hidden behind the borehole casing.

Borehole casing properties of interest include casing thickness, material strength and diameter, as these properties can influence options for retrieving emplaced waste canisters from within a borehole. Stronger, more rigid casing could enhance retrievability of canisters by helping to ensure the casing retains its shape and acts as a guide for down-hole retrieval tools. Casing can also mask or obscure certain design features, such a dog leg or other deviations from a declared design, as noted.

Optical and acoustic imaging systems are especially promising DIV inspection tools, although routine use at the depths, temperatures and pressures in the lower reaches of a deep borehole may be restricted by design limits for many COTS video cameras, OTVs and ATVs. Many of these instruments evaluated for this report are designed for inspecting much shallower boreholes and water wells. Despite this potential shortcoming, the advantages of using OTVs to obtain detailed, high-resolution optical images of a borehole and casing suggest these tools show considerable promise as DIV inspection tools, at least for the upper reaches of a borehole, and some may be modifiable to operate at greater depths.

Casing diameter can be routinely measured with COTS cased-hole calipers, notably MFCs, which operate in air and at temperatures and pressures expected at 5 km depth. Magnetic flux leakage (MFL) tools are considered most applicable to locating large-scale defects in casing, such as missing pipe sections, as well as changes in casing properties that might indicate a change in casing material. Detecting a section of missing cement (a gap) could indicate a potential side hole or dog leg hidden behind the borehole casing. This would seem a straightforward application of acoustic scanners (CBL tools), and well within the capabilities of COTS instruments. However, the need to perform acoustic measurements within a coupling medium, such as mud or water, would obviate this method's applicability in air-filled boreholes.

Borehole trajectory can be determined for a cased hole with a variety of directional-survey instruments. It may be sufficient for DIV purposes to verify a borehole's inclination (i.e., vertical). Numerous MFCs come equipped with inclinometers. More detailed characterization of a borehole's trajectory, which may be necessary if inclination is found to deviate from vertical, would require measuring inclination and azimuth, which is best accomplished in a cased hole by using gyroscopic-based survey instruments.

Many borehole instruments require a borehole fluid be present (e.g., acoustic imagers and EM scanners), and so cannot be used to inspect air-filled boreholes. Furthermore, many of these fluid-dependent

instruments have capabilities that can identify possible missing cement (gaps) or side holes hidden behind casing. Equipment that can operate in air-filled boreholes is more limited, and none evaluated here are considered well suited for identifying gaps in cement or other features hidden behind casing. Table 12 lists COTS tools that might be used to glean information relevant to DIV inspections according to ambient borehole environment (air or fluid) in which these tools can operate.

Table 12. Potential DIV inspection tools and applicable borehole environments

Inspection parameter	Air & Clear Water	Drilling Mud
Borehole images	Optical video cameras Optical Televiewers	Acoustic Televiewers
Casing/Borehole Diameter	Multi-finger Calipers	Multi-finger Calipers Acoustic & (most) EM scanners
Casing & Cement properties*	Magnetic flux leakage tools (casing thickness) (some) electromagnetic scanners	MFL ultrasonic cement-bond logging tools
Borehole trajectory	Multi-finger Calipers w/ inclinometer Gyroscopes Magnetometers (w/o casing)	Multi-finger Calipers w/ inclinometer Gyroscopes Magnetometers (w/o casing)

* An evaluation of cement properties (cement-bond logging) might reveal hidden gaps or side holes.

In addition to design and construction of individual boreholes, designs of disposal canisters and surface facilities at a DBD site are also of interest for DIV, as well as facilities and equipment associated with emplacement operations and borehole and site closure. Canister design specifications would be verified against a State’s declarations, most effectively by visual examination of unfilled canisters and reverification of canisters being emplaced (e.g., by canister identification markings or other verifiable characteristics). Verifying design features of backfill and seals after a borehole has been closed and sealed would be an unprecedented demand on DIV, as no known equipment could readily interrogate backfill and seals in a closed borehole. Verification of seals may be limited to inspection at the surface and observation of seals being installed in the borehole. For a DBD facility with a multiple-borehole array, individual boreholes may be in various states of operation: drilling, emplacement, closure and sealing, so that DIV inspections would be required for multiple boreholes, concurrently or consecutively.

8.1. Recommendations

Determine DIV inspection requirements and contingency plans. In order to identify the most appropriate tools for use in a DIV inspection, inspection requirements need to be established. For example, will a survey of the completed borehole with installed casing provide sufficient information for an unambiguous conclusion to be drawn? Will information about a borehole’s construction be needed before completion? If so, how is that information to be obtained (e.g., sharing operator equipment during MWD or interrupting drilling operations for independent inspections)? If a question arises from DIV information obtained, what additional information will be needed to draw a firm conclusion? What

additional equipment (or different survey methodology) can obtain the necessary information? Answers to questions such as these will help determine which tools are needed to provide necessary information at the appropriate time.

We have tacitly assumed for this report that DIV inspections are likely to be performed after a borehole has been completed and the casing installed. The environment considered most likely during a post-completion DIV inspection is an air-filled borehole, severely limiting tools available for in-depth examination of casing and cement properties (potentially making the detection of gaps or side holes more challenging). An operator's drilling plans could impact such an assumption. For example, if a borehole is drilled with the use of drilling mud, a DIV inspection might be performed before the mud is removed, using appropriate acoustic and electromagnetic (EM) scanners; then a final (separate) optical inspection of the borehole might be conducted after mud has been removed.

Use compatible instruments in a single down-hole inspection tool when possible. Because of the time and effort associated with handling borehole inspection equipment (including hauling from on-site storage to a borehole and lowering on a wireline) a single downhole probe with multiple inspection tools is desirable, maximizing information gleaned from a single inspection survey or trip.

For example, if inspecting an air-filled borehole after completion, we recommend a multi-finger caliper (MFC) equipped with optical video camera plus inclinometer. Such a tool would provide visual information about the inner casing while recording casing diameter and inclination. The possibility of including a magnetic flux leakage (MFL) tool with air-capable EM scanner on the same probe would further increase efficiency and provide additional information about casing properties (thickness, gaps and material properties) as well as identifying gaps behind casing. It is unclear from our analysis that such a multi-tool is feasible (this would need confirmation from tool suppliers), but it is not uncommon to deploy more than one instrument in a single wireline trip.

Use operator-owned hauling, hoisting and wireline equipment. COTS tool weights can range from a few tens of kg to more than 100 kg, and tool lengths can reach 5 or 10 m (or more), making the handling of most inspection tools by individuals difficult or impossible, and potentially dangerous. Most COTS inspection tools require special hoisting and hauling equipment; however, such equipment is likely to be available at the drilling site, owned or leased by the drilling operator. Rather than purchasing hoisting and hauling equipment for dedicated use by DIV inspectors, entering an agreement with the operator to share such equipment seems a clear choice, especially as such equipment does not impact measurements. In addition, most inspection tools evaluated for this report are deployed downhole on a wireline (or slick line), also likely to be in use on site by the operator. Shared use of wireline that contains telemetry for communications may require special arrangements or modifications for inspection tools using a shared wireline. Where possible, tools that store data in memory downhole for later downloading to a computer at the surface are recommended for DIV inspections.

Combine remote sensing at a DBD facility with DIV inspections of individual boreholes. The ability to detect all possible undeclared design features in a completed borehole is unlikely to be straightforward, even with state-of-the-art inspection tools. Remote sensing of drilling activities during the construction and operation of a DBD facility can provide additional assurance about the absence of undeclared design variations and improve confidence in the ability to detect them. Seismic/acoustic monitoring of drilling activities, in particular, is recommended as a complement to individual borehole inspection.

Consult with borehole inspection-service providers. Many borehole-inspection tools evaluated for this report use technologies that require special knowledge and training to operate safely and effectively and to interpret data appropriately. Numerous borehole logging and inspection services are available, and have expertise and experience with a wide variety of borehole evaluations.²⁹ We recommend that the inspectorate consult one or more such service providers for advice on tool use and possible training for DIV inspectors.

This recommendation brings us to another possibility, which is to out-source DIV inspections to an independent service provider.

Alternative Option: Use a commercial logging and borehole-inspection service for DIV inspections.

Given the number of companies that provide professional borehole logging and inspection services, combined with training, handling and other requirements for proper tool use, it seems prudent to explore the possibility of hiring a well-logging service provider with appropriate experience and expertise to conduct DIV inspections. This may break from existing DIV safeguards practice and would require appropriate arrangements. Nevertheless, if possible to implement, this option could significantly increase confidence in obtaining reliable DIV information with minimal effort, delay or disruption in the field.

Explore novel technologies for DIV inspections of deep boreholes. Despite the range and variety of COTS borehole inspection and logging tools, certain unique demands for DIV inspections may not be fully addressed by current COTS technologies, as some tools might be used to glean information they are not really designed to extract. Applying technologies used for other applications to borehole DIV inspections could prove promising. For example, ground-penetrating radar might effectually detect gaps and side holes in an air-filled borehole, provided such equipment could be integrated into a downhole probe. Another example, might be using a modified IR (infra-red) range finder to probe borehole diameter or other casing features of interest for DIV inspections. In fact, testing COTS borehole-inspection tools under realistic condition could reveal potential gaps in DIV information.

²⁹ A list of well-logging service companies is available from the Oildex web site (<https://www.oildex.com/resources/directory/service-companies/#well-logging>), although no attempt was made by us to assure all information on that site is correct or complete.

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APPENDIX A. TECHNICAL REQUIREMENTS OF THE REFERENCE DESIGN

The reference design for a DBD system used in this report (Arnold B. W., et al., 2011) assumes that each borehole will 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). Essential technical requirements for a borehole are described below, based on the reference design.³⁰

- 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.

³⁰ Taken from (Arnold B. W., et al., 2011).

APPENDIX B. BOREHOLE AND FORMATION INSPECTION TOOLS ³¹

<i>Company Name</i>	<i>Tool Code</i>	<i>Tool Description</i>
BAKER ATLAS WIRELINE	3DEX	3D Induction Logging Service
BAKER ATLAS WIRELINE	AC	BHC Acoustilog
BAKER ATLAS WIRELINE	AZITRAK	Deep Azimuthal Propagation Resistivity
BAKER ATLAS WIRELINE	CAL	Caliper
BAKER ATLAS WIRELINE	CBIL	Circumferential Borehole Imaging Log
BAKER ATLAS WIRELINE	CDL	Compensated Density Log
BAKER ATLAS WIRELINE	CN	Compensated Neutron Log
BAKER ATLAS WIRELINE	DAC	Digital Array Acoustilog
BAKER ATLAS WIRELINE	DAL	Digital Acoustilog
BAKER ATLAS WIRELINE	DEL2	Dielectric Log - 200 Mhz
BAKER ATLAS WIRELINE	DEL4	Dielectric Log - 47 Mhz
BAKER ATLAS WIRELINE	DIFL	Dual Induction Focused Log
BAKER ATLAS WIRELINE	DIP	High Resolution 4-Arm Diplog
BAKER ATLAS WIRELINE	DLL	Dual Laterolog
BAKER ATLAS WIRELINE	DPIL	Dual Phase Induction Log
BAKER ATLAS WIRELINE	DSL	Spectral Gamma Ray
BAKER ATLAS WIRELINE	EI	Earth Imager
BAKER ATLAS WIRELINE	FLEX	Spectroscopy
BAKER ATLAS WIRELINE	FMT	Formation Multi-Tester
BAKER ATLAS WIRELINE	FTeX	Formation Pressure Tester
BAKER ATLAS WIRELINE	GEM	Gamma Element Minerology
BAKER ATLAS WIRELINE	GEOEX	Geo Explorer Imaging Tool
BAKER ATLAS WIRELINE	GR	Gamma Ray
BAKER ATLAS WIRELINE	HDIL_BA	High-Definition Induction Log
BAKER ATLAS WIRELINE	HDIP	Hexagonal Diplog
BAKER ATLAS WIRELINE	HDLL	High-Definition Lateral Log
BAKER ATLAS WIRELINE	ICAL	Imaging Caliper
BAKER ATLAS WIRELINE	IEL	Induction Electrolog
BAKER ATLAS WIRELINE	ISSB	Isolation Sub - Spontaneous Potential
BAKER ATLAS WIRELINE	MAC	Multipole Array Acoustilog
BAKER ATLAS WIRELINE	MAC2	Multipole Array Acoustilog

³¹ Compiled by The Bureau of Safety and Environmental Enforcement (BSEE) March 2016
[\(https://www.bsee.gov/\)](https://www.bsee.gov/).

BAKER ATLAS WIRELINE	MaxCOR	Large Diameter Rotary Sidewall Core
BAKER ATLAS WIRELINE	MFC	Multi-Finger Caliper
BAKER ATLAS WIRELINE	ML	Minilog
BAKER ATLAS WIRELINE	MLL	Micro Laterolog
BAKER ATLAS WIRELINE	MREX	Magnetic Resonance Explorer Imaging Log
BAKER ATLAS WIRELINE	MRIL	Magnetic Resonance Imaging Log
BAKER ATLAS WIRELINE	MSL	Micro Spherical Laterolog
BAKER ATLAS WIRELINE	ORIT	Directional Survey
BAKER ATLAS WIRELINE	PDK	PDK-100
BAKER ATLAS WIRELINE	PROX	Proximity Log
BAKER ATLAS WIRELINE	RCI	Reservoir Characterization Instrument
BAKER ATLAS WIRELINE	RCOR	Rotary Sidewall Coring Tool
BAKER ATLAS WIRELINE	RCX	Reservoir Characterization eXplorer/Sentinel Focused Sampler
BAKER ATLAS WIRELINE	RIL	Resistivity Imaging Log
BAKER ATLAS WIRELINE	RPM	Reservoir Performance Monitor
BAKER ATLAS WIRELINE	SBT	Segmented Bond Tool
BAKER ATLAS WIRELINE	SL	Spectralog
BAKER ATLAS WIRELINE	SP	Spontaneous Potential
BAKER ATLAS WIRELINE	STAR	Simultaneous Acoustic and Resistivity Imager
BAKER ATLAS WIRELINE	SWC	Sidewall Coregun
BAKER ATLAS WIRELINE	SYST	Surface System
BAKER ATLAS WIRELINE	TBRT	Thin-Bed Resistivity
BAKER ATLAS WIRELINE	TTRM	Temperature/Tension/Mud Resistivity Sub
BAKER ATLAS WIRELINE	VS	Velocity Survey
BAKER ATLAS WIRELINE	VSP	Vertical Seismic Profile
BAKER ATLAS WIRELINE	WGI	Well Geometry Instrument
BAKER ATLAS WIRELINE	WTS	ECLIPS WTS Downhole Common Remote
BAKER ATLAS WIRELINE	XMAC	Cross-Multipole Array Acoustilog
BAKER ATLAS WIRELINE	XMAC-E	XMAC Elite (Next generation XMAC)
BAKER ATLAS WIRELINE	ZDL	Compensated Z-Densilog
BAKER INTEQ	AP	Annular Pressure
BAKER INTEQ	APR	Azimuthal Propagation Resistivity
BAKER INTEQ	APX	Acoustic Porosity Explorer
BAKER INTEQ	AZTK	Azimuthal Propagation Resistivity
BAKER INTEQ	CCN	Caliper Corrected Neutron
BAKER INTEQ	COP	Drilling Dynamics

BAKER INTEQ	DCP	Annular Pressure
BAKER INTEQ	DIR	Directional
BAKER INTEQ	DPR	Dual Propagation Resistivity
BAKER INTEQ	DPRT	Deep Propagation Resistivity
BAKER INTEQ	DTK	Deep Propagation Resistivity
BAKER INTEQ	FMT	Formation Multi-Tester
BAKER INTEQ	FTK	Formation Fluid Sampling
BAKER INTEQ	GAM	Gamma Ray
BAKER INTEQ	GR	Gamma Ray
BAKER INTEQ	LTK	Advanced LWD Porosity
BAKER INTEQ	MAGTRAK	NMR MagTrak
BAKER INTEQ	MDL	Modular Density Lithology
BAKER INTEQ	MNP	Modular Neutron Porosity
BAKER INTEQ	MPR	Multiple Propagation Resistivity
BAKER INTEQ	MRT	Magnetic Resonance
BAKER INTEQ	MTK	Magnetic Resonance
BAKER INTEQ	NBIG	Near Bit Gamma Ray
BAKER INTEQ	NC	Navigamma
BAKER INTEQ	NT	NaviTrak
BAKER INTEQ	ORD	Compensated Bulk Density
BAKER INTEQ	OTK	OnTrak
BAKER INTEQ	RIT	Resistivity Imaging
BAKER INTEQ	RNT	Multiple Propagation Resistivity
BAKER INTEQ	SDTK	Acoustic
BAKER INTEQ	STK	Azimuthal Resistivity Imaging
BAKER INTEQ	TesTrak	Formation Pressure Tester-While-Drilling
BAKER INTEQ	TT	Formation Tes Trak
BAKER INTEQ	TTK	Tes Trak Formation Tester
BAKER INTEQ	USMPR	UltraSlim Multiple Propagation Resistivity
BAKER INTEQ	VSS	Vibration and Stick Slip
BAKER INTEQ	ZTK	Bit Resistivity
COMPUTALOG	AZD	Azimuthal Density
COMPUTALOG	BCS	Borehole Compensated Sonic
COMPUTALOG	CAL	Caliper
COMPUTALOG	CDT	Compensated Density
COMPUTALOG	CNT	Compensated Neutron

COMPUTALOG	DAR	Digital Acoustic Tool
COMPUTALOG	DLL	Dual Laterolog
COMPUTALOG	DTD	Tension Compression
COMPUTALOG	FED	Four Electrode Dipmeter
COMPUTALOG	GR	Gamma Ray
COMPUTALOG	GRN	Gamma Ray Neutron
COMPUTALOG	HADR	High Temperature Azimuthal Gamma Ray
COMPUTALOG	HBC	High Resolution Borehole Sonic
COMPUTALOG	HMI	High Resolution Micro Imager
COMPUTALOG	IEL	Induction Electric Log
COMPUTALOG	MAN	Multi Array Neutron
COMPUTALOG	MDA	Monopole Dipole Acoustic
COMPUTALOG	MEL	Micro Electric Log
COMPUTALOG	MFR	Multi Frequency Resistivity
COMPUTALOG	MRT400	Micro Resistivity Tool
COMPUTALOG	MSC	Multi Sensor Caliper
COMPUTALOG	MSFL	Micro Spherically Focused Log
COMPUTALOG	NMRT	Nuclear Magnetic Resonance Tool
COMPUTALOG	NTT	Single Detector Neutron
COMPUTALOG	PND	Pulsed Neutron Decay
COMPUTALOG	RSCT	Rotary Sidewall Coring Tool
COMPUTALOG	SAGR	Spectral Azimuthal Gamma Ray
COMPUTALOG	SED	Six Electrode Dipmeter
COMPUTALOG	SFT	Selective Formation Tester
COMPUTALOG	SGR	Spectral Gamma Ray
COMPUTALOG	SP	Spontaneous Potential
COMPUTALOG	SPeD	Spectral Pe Density
COMPUTALOG	STI	Simultaneous Triple Induction
COMPUTALOG	TEN	Tension
COMPUTALOG	TNP	Thermal Neutron Porosity
HALLIBURTON	ACRT	Array Combination Resistivity Tool
HALLIBURTON	BCS	Borehole Compensated Sonic
HALLIBURTON	BHPT	Borehole Properties Tool
HALLIBURTON	CAST	Circumferential Acoustic Scanning
HALLIBURTON	CDL	Compensated Density Log
HALLIBURTON	CSNG	Compensated Spectral Natural Gamma Ray

HALLIBURTON	DHT	Downhole Tension
HALLIBURTON	DIL	Dual Induction Log
HALLIBURTON	DLLT	Dual Laterolog
HALLIBURTON	DSN	Dual Spaced Neutron
HALLIBURTON	EMI	Electrical Micro Imaging
HALLIBURTON	FIAC	Four Independent Arm Caliper
HALLIBURTON	FWS	Full Wave Sonic
HALLIBURTON	GAMMA	Gamma Ray
HALLIBURTON	GR	Gamma Ray
HALLIBURTON	HDIL_HAL	Hostile Dual Induction
HALLIBURTON	HDTD	Hostile Downhole Tension
HALLIBURTON	HFDT	High Frequency Dielectric
HALLIBURTON	HRAI	High Resolution Array Induction Log
HALLIBURTON	HRI	High Resolution Induction (includes HRAI)
HALLIBURTON	HSN	Hostile Short Normal
HALLIBURTON	IDT	LOGIQ Directional Tool
HALLIBURTON	LL3	Laterolog 3
HALLIBURTON	LSS	Long Spaced Sonic
HALLIBURTON	MACT	Multi-Arm Caliper Tool
HALLIBURTON	MICLOG	Microlog
HALLIBURTON	MRIL	Magnetic Resonance Imaging Log
HALLIBURTON	MSFL	Micro-Spherically Focused Log
HALLIBURTON	NGRT	Gamma Ray Tool
HALLIBURTON	OMRI	Oil Mud Reservoir Imaging Tool
HALLIBURTON	RDT	Reservoir Description Tool
HALLIBURTON	RSCT	Rotary Sidewall Coring
HALLIBURTON	SDL	Spectral Density Log
HALLIBURTON	SED	Six Arm Dipmeter
HALLIBURTON	SFT	Sequential Formation Tester
HALLIBURTON	SGR	Spectral Gamma Ray
HALLIBURTON	SP	Spontaneous Potential
HALLIBURTON	TMD-L	Thermal Multigate Decay-Lithology
HALLIBURTON	WSCD	Wave Sonic Cross Dipole
HALLIBURTON	WSD	WaveSonic Dipole
HALLIBURTON	XRMI	X-tended Range Micro Imager Tool
HALLIBURTON	XYC	XY Caliper Log

HALLIBURTON SPERRY SUN	!BG™	At-Bit Gamma Ray
HALLIBURTON SPERRY SUN	ACAL	AcoustiCaliper
HALLIBURTON SPERRY SUN	!DR™	Azimuthal Deep Resistivity
HALLIBURTON SPERRY SUN	!FR™	Azimuthal Focused Resistivity
HALLIBURTON SPERRY SUN	AGR	Azimuthal Gamma Ray
HALLIBURTON SPERRY SUN	ALD	Azimuthal Litho Density
HALLIBURTON SPERRY SUN	ASLD	Azimuthal Stabilized Litho Density
HALLIBURTON SPERRY SUN	BAT	Bi-Modal Acoustic Tool
HALLIBURTON SPERRY SUN	CNP	Compensated Neutron Porosity
HALLIBURTON SPERRY SUN	CTN	Compensated Thermal Neutron
HALLIBURTON SPERRY SUN	DDS	Drilling Dynamics Sensor
HALLIBURTON SPERRY SUN	DGR	Dual Gamma Ray
HALLIBURTON SPERRY SUN	DIR	Directional
HALLIBURTON SPERRY SUN	DrillDOC™	Drilling Downhole Optimization Collar
HALLIBURTON SPERRY SUN	EWP4	EWR - Phase 4
HALLIBURTON SPERRY SUN	EWR-M5	EWR-M5 Resistivity
HALLIBURTON SPERRY SUN	EWR-P4	EWR-Phase 4 Resistivity
HALLIBURTON SPERRY SUN	EWR-P4D	EWR-Phase 4D Resistivity
HALLIBURTON SPERRY SUN	EWRS	Electromagnetic Wave Resistivity (Shielded)
HALLIBURTON SPERRY SUN	FTWD	Formation Test While Drilling
HALLIBURTON SPERRY SUN	G!BI™	Gamma Ray and At-Bit Inclination
HALLIBURTON SPERRY SUN	GeoTap	GeoTap Formation Tester
HALLIBURTON SPERRY SUN	GEOTAPID	GeoTap IDS
HALLIBURTON SPERRY SUN	GM	Gamma Module
HALLIBURTON SPERRY SUN	GPGR	Geo-Pilot Azimuthal Gamma Ray
HALLIBURTON SPERRY SUN	IVSS	Insert Vibration Severity Sensor
HALLIBURTON SPERRY SUN	MRIL-WD	Magnetic Resonance Image Logging
HALLIBURTON SPERRY SUN	NGP	Natural Gamma Probe
HALLIBURTON SPERRY SUN	NUCP	Smoothed Neutron Porosity
HALLIBURTON SPERRY SUN	PCAL	Pinger Caliper (Mounted on ALD)
HALLIBURTON SPERRY SUN	PCD	Pressure Case Directional
HALLIBURTON SPERRY SUN	PCG	Pressure Case Gamma
HALLIBURTON SPERRY SUN	PM	Position Monitor
HALLIBURTON SPERRY SUN	PPFG	Pore Pressure/Fracture Gradient
HALLIBURTON SPERRY SUN	PWD	Pressure While Drilling
HALLIBURTON SPERRY SUN	S175	Solar 175

HALLIBURTON SPERRY SUN	SFD	Simultaneous Formation Density
HALLIBURTON SPERRY SUN	SLD	Stabilized Litho Density
HALLIBURTON SPERRY SUN	SP4™	Slim Electromagnetic Wave Resistivity – Phase 4
HALLIBURTON SPERRY SUN	SSEWR-P4	SuperSlim EWR-Phase 4
HALLIBURTON SPERRY SUN	SSP4™	Super Slim Electromagnetic Wave Resistivity – Phase 4
HALLIBURTON SPERRY SUN	SVSS	Sonde Vibration Severty Sensor
HALLIBURTON SPERRY SUN	UHT	Prometheus™ (Ultra High Temperature)
HALLIBURTON SPERRY SUN	XHT	XHT 200 Hot Hole
PATHFINDER LOGGING	AWR	Array Wave Resistivity/Gamma Ray
PATHFINDER LOGGING	CLSSM	Compensated Long Spaced Sonic MultiLink
PATHFINDER LOGGING	CWRGM	Compensated Wave Resistivity Gamma MultiLink
PATHFINDER LOGGING	DFT	Dynamic Formation Tester
PATHFINDER LOGGING	DIR	Directional
PATHFINDER LOGGING	DNSCM	Density Neutron Standoff Caliper MultiLink
PATHFINDER LOGGING	DPM	Dynamic Pressure Module
PATHFINDER LOGGING	GAM	Gamma Ray Sonde
PATHFINDER LOGGING	GyroHDS1	Gyro High-Speed Directional Survey
PATHFINDER LOGGING	HDS1L	High-Speed Directional Survey
PATHFINDER LOGGING	HDS1R	High-Speed Directional Survey Retrievable
PATHFINDER LOGGING	HDSM	High-Speed Directional Survey MultiLink
PATHFINDER LOGGING	PWD	Pressure While Drilling
PATHFINDER LOGGING	PZIG	At-Bit Inclination and Gamma Ray
PATHFINDER LOGGING	QPM	Survivor Dynamic Pressure Module
PATHFINDER LOGGING	SAWR	Slim Array Wave Resistivity/Gamma Ray
PATHFINDER LOGGING	SCLSS	Slim Compensated Long Spaced Sonic
PATHFINDER LOGGING	SCWR	Slim Compensated Wave Resistivity
PATHFINDER LOGGING	SDNSC	Slim Density Neutron Standoff Caliper
PRECISION ENERGY	AZD	Azimuthal Density
PRECISION ENERGY	BAP	Bore/Annular Pressure
PRECISION ENERGY	BCS	Borehole Compensated Sonic
PRECISION ENERGY	CALI	General Caliper
PRECISION ENERGY	CNS	Compensated Neutron Service
PRECISION ENERGY	CNT	Compensated Neutron Tool
PRECISION ENERGY	DLL	Dual Laterolog
PRECISION ENERGY	ESM	Environmental Severty Measurement
PRECISION ENERGY	FCAL	Single Axis Caliper

PRECISION ENERGY	FRT	Flow Rate Tester
PRECISION ENERGY	GR	Gamma Ray
PRECISION ENERGY	HAGR	High Temperature Azimuthal Gamma Ray
PRECISION ENERGY	HBC	High Resolution Borehole Sonic
PRECISION ENERGY	HMI	High Resolution Micro Imager
PRECISION ENERGY	IDS	Integrated Directional Sonde
PRECISION ENERGY	MCG	Compact Gamma
PRECISION ENERGY	MDA	Monopole Dipole Array
PRECISION ENERGY	MDN	Compact Dual Neutron Sonde
PRECISION ENERGY	MFR	Multi-Frequency Resistivity
PRECISION ENERGY	MFT	Compact Repeat Formation Pressure Tester
PRECISION ENERGY	MGS	Auxiliary Gamma Sub
PRECISION ENERGY	MPD	Compact PhotoDensity Sonde
PRECISION ENERGY	MRT	Micro Resistivity Tool
PRECISION ENERGY	MSFL	Micro Spherically Focused Log
PRECISION ENERGY	NMRT	Nuclear Magnetic Resonance Tool
PRECISION ENERGY	RSCT	Rotary Sidewall Coring Tool
PRECISION ENERGY	RTGR	Real Time Gamma Ray
PRECISION ENERGY	SED	Six Electrode Dipmeter
PRECISION ENERGY	SFT	Selective Formation Tester
PRECISION ENERGY	SGR	Spectral Gamma Ray
PRECISION ENERGY	SGS-C	Spectral Gamma Sonde
PRECISION ENERGY	SPeD	Spectral Pe Density
PRECISION ENERGY	STI	Simultaneous Triple Induction
PRECISION ENERGY	SWC	Sidewall Coring Gun
PRECISION ENERGY	TNP	Thermal Neutron Porosity
PRECISION ENERGY	UGR	Universal Gamma Ray
PRECISION ENERGY	VSP	Vertical Seismic Profile
PROTECHNICS	SpectraS	SpectraScan - spectral gamma ray
REEVES WIRELINE	MAI	Compact Array Induction
REEVES WIRELINE	MBN	Compact Borehole Navigator
REEVES WIRELINE	MDL_R	Compact Dual Laterolog Sonde
REEVES WIRELINE	MDN	Compact Dual Neutron
REEVES WIRELINE	MFE	High Resolution Shallow Focused Electric
REEVES WIRELINE	MFT	Compact Repeat Formation Pressure Tester
REEVES WIRELINE	MGS	Auxiliary Gamma Sub

REEVES WIRELINE	MML	Compact Microlog
REEVES WIRELINE	MMR	Compact Microlaterolog
REEVES WIRELINE	MPD	Compact PhotoDensity
REEVES WIRELINE	MSS	Compact Sonic Sonde
REEVES WIRELINE	MTC	Compact Two Arm Caliper
REEVES WIRLINE	MCG	Compact Gamma
SCHLUMBERGER	AACT	Aluminium Activation Clay Tool
SCHLUMBERGER	ACT	Geochemical Logging Tool
SCHLUMBERGER	ADN	Azimuthal Density Neutron
SCHLUMBERGER	AGS	Aluminium Gamma Ray Spectroscopy Sonde
SCHLUMBERGER	AIT	Array Induction Imager
SCHLUMBERGER	ALAT	Azimuthal Laterolog
SCHLUMBERGER	AMS	Auxiliary Measurement Sonde
SCHLUMBERGER	APS	Accelerator Porosity Sonde
SCHLUMBERGER	APWD	Annular Pressure While Drilling
SCHLUMBERGER	APWDTL	Annular Pressure While Drilling Time Log
SCHLUMBERGER	ARC	Array Compensated Resistivity
SCHLUMBERGER	BHTV	Borehole Televierwer
SCHLUMBERGER	BSP	Bridle Spontaneous Potential
SCHLUMBERGER	CALI	Generalized Caliper
SCHLUMBERGER	CBTT	Combinable Borehole Televierwer Tool
SCHLUMBERGER	CDN	Compensated Density Neutron
SCHLUMBERGER	CDR	Compensated Dual Resistivity
SCHLUMBERGER	CHFR	Cased Hole Formation Resistivity
SCHLUMBERGER	CHFT	Cased Hole Dynamics Tester
SCHLUMBERGER	CMR	Combinable Magnetic Resonance
SCHLUMBERGER	CNL	Compensated Neutron Log
SCHLUMBERGER	CNT	Compensated Neutron Tool
SCHLUMBERGER	CNTS	Slim Compensated Neutron Tool
SCHLUMBERGER	CST	Core Sample Taker; Chronological Sample Taker
SCHLUMBERGER	DEV	Continuous Directional Survey
SCHLUMBERGER	DFR	VISION Dual Frequency Resistivity
SCHLUMBERGER	DGR	Dual Gamma Ray
SCHLUMBERGER	DIR	Directional
SCHLUMBERGER	DIT	Dual Induction
SCHLUMBERGER	DLT	Dual Laterolog

SCHLUMBERGER	DPT	Deep Propagation Tool
SCHLUMBERGER	DSI	Dipole Shear Sonic Imager
SCHLUMBERGER	DSL	Digitizing Sonic Logging
SCHLUMBERGER	DSST	Dipole Shear Sonic Imager
SCHLUMBERGER	DST	Dual Laterolog with SRT
SCHLUMBERGER	DWST	Digital Waterform Sonic
SCHLUMBERGER	ECO	Ecoscope
SCHLUMBERGER	ECS	Elemental Capture Spectroscopy Sonde
SCHLUMBERGER	EDTC	Telemetry Cartridge
SCHLUMBERGER	EMS	Environmental Measurement Sonde
SCHLUMBERGER	ETP	Electromagnetic Propagation (ADEPT)
SCHLUMBERGER	ES	Electrical Survey Tool
SCHLUMBERGER	FBST	Fullbore Formation Micro Imager
SCHLUMBERGER	FGT	Formation Gamma Gamma
SCHLUMBERGER	FMI	Fullbore Formation Micro Imager
SCHLUMBERGER	FMS	Formation Micro Scanner
SCHLUMBERGER	FPWD	Formation Pressure While Drilling
SCHLUMBERGER	GFA	Formation Tester Gamma Ray Detector
SCHLUMBERGER	GFT	Formation Tester Gamma Ray
SCHLUMBERGER	GNT	Gamma Neutron Tool
SCHLUMBERGER	GPIT	General Purpose Inclination Tool
SCHLUMBERGER	GR	Gamma Ray
SCHLUMBERGER	GRA	Geochemical Reservoir Analyzer
SCHLUMBERGER	GRST	Gamma Ray Spectrometry Tool
SCHLUMBERGER	GRT	Gamma Ray Tool
SCHLUMBERGER	GST	Geo-Steering Tool
SCHLUMBERGER	GVR	GeoVision Resistivity
SCHLUMBERGER	H4TG	Hostile Telemetry/Gamma Ray
SCHLUMBERGER	HALS	High Resolution Azimuthal Laterolog Sonde
SCHLUMBERGER	HAPS	HPHT Accelerator Porosity Sonde (aka XAPS)
SCHLUMBERGER	HCAL	Single Axis Caliper
SCHLUMBERGER	HDNT	Hostile Density/Neutron
SCHLUMBERGER	HDT	High Resolution Dipmeter
SCHLUMBERGER	HGNS	HILT Gamma Ray Neutron Sonde
SCHLUMBERGER	HILT	High Integrated Logging Tool
SCHLUMBERGER	HIT	Hostile Array Induction Tool (aka XAIT)

SCHLUMBERGER	HLDS	Hostile Litho-Density Sonde
SCHLUMBERGER	HLDT	Hostile Environment Litho-Density
SCHLUMBERGER	HNGS	Hostile Gamma Ray Neutron Sonde
SCHLUMBERGER	HNGT	Hostile Natural Gamma Ray Spectrometry
SCHLUMBERGER	HRCC	High Resolution Control Cartridge
SCHLUMBERGER	HRDD	HILT High Resolution Density Device
SCHLUMBERGER	HRGD	HILT High Resolution Resistivity Gamma Ray Density Device
SCHLUMBERGER	HRLT	High Resolution Laterolog Array Tool
SCHLUMBERGER	HRMS	High Resolution Measurement Sonde
SCHLUMBERGER	HSGT	Hostile Environment Gamma Ray
SCHLUMBERGER	HSLT	HPHT Digital Sonic Logging Tool (aka XSLT)
SCHLUMBERGER	HTGC	Hostile Environment Intergrated Telemetry & GR Cartridge
SCHLUMBERGER	IES	Induction Electric Survey
SCHLUMBERGER	IMPA	IMPulse Array Compensated Resistivity
SCHLUMBERGER	IPL	Integrated Porosity Lithology
SCHLUMBERGER	IRT	Induction Resistivity Tool
SCHLUMBERGER	ISONIC	LWD Sonic
SCHLUMBERGER	LDS	Litho Density Sonde
SCHLUMBERGER	LDT	Litho Density
SCHLUMBERGER	LSHDS	Litho Scanner High Definition Spectroscopy
SCHLUMBERGER	LSS	Long Spaced Sonic
SCHLUMBERGER	MAXS	MAX Sonic
SCHLUMBERGER	MCFL	Micro-Cylindrically Focused Log
SCHLUMBERGER	MCR_VIS	mcr VISION Resistivity
SCHLUMBERGER	MDLT	Medium Dual Laterolog
SCHLUMBERGER	MDT	Modular Formation Dynamics Tester
SCHLUMBERGER	MLT	Microlog
SCHLUMBERGER	MRPS	Modular Formation Dynamics Tester Single-Probe
SCHLUMBERGER	MRSC	Modular Formation Dynamics Tester Sample Chamber
SCHLUMBERGER	MRWD	Magnetic Resonance While Drilling
SCHLUMBERGER	MRX	Magnetic Resonance eXpert
SCHLUMBERGER	MSCT	Mechanical Sidewall Coring Tool
SCHLUMBERGER	MSIP	Modular Sonic Imaging Platform
SCHLUMBERGER	MWD	Measurement While Drilling

SCHLUMBERGER	NEOSCOPE	Sourceless Formation Evaluation While Drilling
SCHLUMBERGER	NGI	Next Generation Imager
SCHLUMBERGER	NGS	Natural Gamma Ray Sonde
SCHLUMBERGER	NGT	Natural Gamma Ray Spectrometry
SCHLUMBERGER	NMT	Nuclear Magnetism
SCHLUMBERGER	NPLC	Nuclear Porosity Lithology
SCHLUMBERGER	NPLT	Nuclear Porosity Lithology
SCHLUMBERGER	OBDT	Oil Base Mud Dipmeter
SCHLUMBERGER	OBMI	Oil Base Micro Imager
SCHLUMBERGER	OBMI2	Dual Oil Based Micro Imager
SCHLUMBERGER	OBMT	Oil Base Mud Formation Imager
SCHLUMBERGER	OMRI	Oil Based Mud Imager
SCHLUMBERGER	PERI	Periscope
SCHLUMBERGER	PEX	Platform Express
SCHLUMBERGER	PGT	Compensated Density
SCHLUMBERGER	PMIT	PS Platform Multifinger Imaging Tool
SCHLUMBERGER	PNT	Sidewall Neutron Tool
SCHLUMBERGER	PPC	Powered Positioning Device & Caliper
SCHLUMBERGER	PSCT	Percussion Sidewall Core Tool
SCHLUMBERGER	QAIT	Slim Hostile Array Induction Tool
SCHLUMBERGER	QAST	Q Analog Seismic Tool
SCHLUMBERGER	QCNT	Slim Hot Compensated Neutron Tool
SCHLUMBERGER	QLDT	Slim Xtreme Litho-Density Tool
SCHLUMBERGER	QSCS	Slimhole Power Caliper Sonde
SCHLUMBERGER	QSLT	Slim Xtreme Sonic Logging Tool
SCHLUMBERGER	QTGC	SlimXtreme Telemetry and Gamma Ray
SCHLUMBERGER	RAB	Resistivity at Bit; Azimuthal Laterolog - Gamma Ray (aka GVR)
SCHLUMBERGER	RFT	Repeat Formation Tester
SCHLUMBERGER	RST	Reservoir Saturation Tool
SCHLUMBERGER	RTSCAN	RTScanner
SCHLUMBERGER	SADN	Segmented Azimuthal Density Neutron
SCHLUMBERGER	SAIT	Slimhole Array Induction
SCHLUMBERGER	SDT	Sonic Digital
SCHLUMBERGER	SGR	Spectral Gamma Ray
SCHLUMBERGER	SGT	Scintillation Gamma Ray
SCHLUMBERGER	SHARP	Slim Hole Retrievable MWD Tool

SCHLUMBERGER	SHDT	Stratigraphic High Resolution Dipmeter Tool
SCHLUMBERGER	SHORT475	Short Pulse Gamma Ray
SCHLUMBERGER	SLDT	Slimhole Litho-Density
SCHLUMBERGER	SLIM1	Slim Hole Retrievable MWD Tool
SCHLUMBERGER	SLT	Borehole Compensated Sonic Logging Tool
SCHLUMBERGER	SMRT	Slim Micro Resistivity Tool
SCHLUMBERGER	SNPD	Sidewall Neutron Tool
SCHLUMBERGER	SONIC	Sonic
SCHLUMBERGER	SONSCAN	Sonic Scanner
SCHLUMBERGER	SONSCOPE	Multipole Sonic-While-Drilling
SCHLUMBERGER	SON-VIS	SonicVISION
SCHLUMBERGER	SP	Spontaneous Potential
SCHLUMBERGER	SPE	SP Extender
SCHLUMBERGER	SPULSE	Slim Pulse MWD Directional
SCHLUMBERGER	SRFT	Slim Repeat Formation Tester
SCHLUMBERGER	SRT	Microspherically Focused Resistivity
SCHLUMBERGER	SSLT	Slim Array Sonic Logging Tool
SCHLUMBERGER	STETHO	Stethoscope
SCHLUMBERGER	STGC	Slim Telemetry and Gamma Ray Cartridge
SCHLUMBERGER	SVWD	Seismic Vision While Drilling
SCHLUMBERGER	TDT	Thermal Decay Time
SCHLUMBERGER	TELE	Telescope
SCHLUMBERGER	TLD	Three-Detector Lithology Density
SCHLUMBERGER	TPT	Temperature and Pressure Tool
SCHLUMBERGER	UBI	Ultrasonic Borehole Imager
SCHLUMBERGER	USIT	Ultrasonic Imager Tool
SCHLUMBERGER	VIPER	VIPER Slimhole Coiled Tubing MWD Tool
SCHLUMBERGER	VISP	Vertical Incident Seismic Profile
SCHLUMBERGER	VPWD	Vision Pressure While Drilling
SCHLUMBERGER	VR	VISION Resistivity
SCHLUMBERGER	VSI	Borehole Seismic Acquisition Tool
SCHLUMBERGER	VSP	Vertical Seismic Profile
SCHLUMBERGER	WAVSP	Walk Away Vertical Seismic Profile
SCHLUMBERGER	XL-ROCK	Large Volume Rotary Sidewall Core
SCHLUMBERGER	XPT	Express Pressure Tester
SCHLUMBERGER	ZAIT	Array Induction Tool

SCIENTIFIC DRILLING	GMWD	Gyro Measure While Drilling
SCIENTIFIC DRILLING	PRT	Propagation Resistivity Tool
WEATHERFORD	AZD	Azimuthal Density
WEATHERFORD	BAP	Bore/Annular Pressure
WEATHERFORD	BCS	Borehole Compensated Sonic
WEATHERFORD	ATV	BondView™ Acoustic Televiewer
WEATHERFORD	ATV	UltraView™ Acoustic Televiewer
WEATHERFORD	CAL	Caliper
WEATHERFORD	CALI	Generalized Caliper
WEATHERFORD	CALVIEW	Multi-arm Multisensory Caliper
WEATHERFORD	CDT	Compensated Density
WEATHERFORD	CMI	Compact Micro Imager
WEATHERFORD	CNS	Compensated Neutron Service
WEATHERFORD	CNT	Compensated Neutron Tool
WEATHERFORD	DAR	Digital Acoustic Tool
WEATHERFORD	DIR	Directional Survey
WEATHERFORD	DLL	Dual Laterolog Log
WEATHERFORD	DTD	Tension Compression
WEATHERFORD	ESM	Environmental Severity Measurement
WEATHERFORD	FCAL	Single Axis Caliper
WEATHERFORD	FED	Four Electrode Dipmeter
WEATHERFORD	FLUXVIEW	Magnetic Flux Leakage Tool
WEATHERFORD	FRT	Flow Rate Tool
WEATHERFORD	GR	Gamma Ray
WEATHERFORD	GRN	Gamma Ray Neutron
WEATHERFORD	GWAR	Guide Wave Azimuthal Resistivity
WEATHERFORD	HAGR	High Temperature Azimuthal Gamma Ray
WEATHERFORD	HBC	High Resolution Borehole Compensated Sonic Log
WEATHERFORD	HMI	High Resolution Micro Imager
WEATHERFORD	IDS	Integrated Directional Sonde
WEATHERFORD	IEL	Induction Electrolog
WEATHERFORD	MAI	Compact Array Induction
WEATHERFORD	MAN	Multi Array Neutron
WEATHERFORD	MBN	Compact Borehole Navigation
WEATHERFORD	MCG	Compact Gamma
WEATHERFORD	MDA	Monopole Dipole Acoustic

WEATHERFORD	MDL_R	Compact Dual Laterolog Sonde
WEATHERFORD	MDN	Compact Dual Neutron
WEATHERFORD	MEL	Micro Electric Log
WEATHERFORD	MFE	High Resolution Shallow Focused Electric
WEATHERFORD	MFR	Multi Frequency Resistivity
WEATHERFORD	MFT	Compact Repeat Formation Pressure Tester
WEATHERFORD	MGS	Auxiliary Gamma Sub
WEATHERFORD	MMR	Compact Microlaterolog
WEATHERFORD	MPD	Compact PhotoDensity
WEATHERFORD	MRT400	Micro Resistivity Tool
WEATHERFORD	MRT-P	Micro Resistivity Tool
WEATHERFORD	MSFL	Micro-Spherically Focused Log
WEATHERFORD	MSS	Compact Sonic Sonde
WEATHERFORD	MTC	Compact Two Arm Caliper
WEATHERFORD	NMRT	Nuclear Magnetic Resonance Tool
WEATHERFORD	NTT	Single Detector Neutron
WEATHERFORD	OBMI	Oil Based Micro Imager
WEATHERFORD	PWFT	Pressure Wave Formation Tester
WEATHERFORD	RESES	Reservoir Evaluation System
WEATHERFORD	RSCT	Rotary Sidewall Coring (HRSC)
WEATHERFORD	SAGR	Spectral Azimuthal Gamma Ray
WEATHERFORD	SED	Six Arm Dipmeter Survey
WEATHERFORD	SFT	Sequential Formation Tester
WEATHERFORD	SGR	Spectral Gamma Ray
WEATHERFORD	SGS-C	Spectral Gamma Sonde
WEATHERFORD	SMI	SineWave Micro Resistivity
WEATHERFORD	SP	Spontaneous Potential
WEATHERFORD	SPED	Spectral Pe Density
WEATHERFORD	SST	Shock Wave Sonic Tool
WEATHERFORD	STI	Simultaneous Triple Induction
WEATHERFORD	SWC	Sidewall Coregun
WEATHERFORD	TEN	Tension
WEATHERFORD	TNP	Thermal Neutron Porosity
WEATHERFORD	UGR	Universal Gamma Ray
WEATHERFORD	VSP	Vertical Seismic Profile

APPENDIX C. DIRECTIONAL SURVEY ERRORS ³²

The accuracy of a borehole survey depends on several factors.

- Accuracy of instrument (sensors, electronics, tolerances)
- Operational accuracy (during survey)
- Calculation
- Location on planet / local environment

A survey instrument's performance depends on the package design elements, calibration performance, and quality control during operation. System performance will depend on borehole inclination, azimuth, geomagnetic-field vector, and geographical position. Because of the dependency on sensing Earth's spin rate, the performance of gyro compassing tools is inversely proportional to the cosine of the latitude of borehole location. A sensor systems' performance generally degrades as inclination increases, especially in an east-west direction at higher latitudes. For magnetic tools, high latitudes have weaker horizontal components of Earth's magnetic field. For two-axis gyro tools, the approach to east/west at high inclinations places the sensor axes increasingly parallel to Earth's spin. With magnetic tools, errors also increase at high east-west inclinations because of the progressive difficulty in compensating for the effect of drill-string magnetism.

Gyro complications

Gyros suffer from an additional uncertainty due to time-related drift. The time component may be significant for gyro systems, especially in horizontal wells. A long survey duration means larger drift uncertainty and longer exposure to the borehole environment, which can reduce the accuracy of directional data. Additionally, gyro performance degrades above 60°, and most gyros cannot be used to survey at inclinations greater than 70° (from vertical).

Tool misalignment

Misalignment of a survey instrument with the borehole results in errors in measuring borehole-axis direction and inclination (inclination and azimuth are both affected). Tool misalignment has long been recognized as a source of significant error in directional surveying.

Error in measured depth

Sources of depth error depend on the type of survey system used. Drill-pipe-conveyed tools (measurement while drilling (MWD), multi-shots, and single-shot) suffer from errors in the physical measurement of drill pipes and the differential effects of drill-string compression and stretch. Because of borehole friction, drill-string compression and stretch are not easily calculated, particularly in inclined wells. Depth errors can account for large angular errors commonly observed when comparing overlapping, high-accuracy surveys in deviated wells.

³² This appendix draws heavily from Chapter 6 in Volume II of The Petroleum Engineering Handbook (Chen 2006).

Wireline survey tools generally have smaller depth errors than drill-string-conveyed tools, provided adequate quality-control measures have been taken. Errors on the order of one part per thousand (0.001) for gyroscopic tools and two parts per thousand (0.002) for drill-string tools are commonly cited, although, these values may not apply to horizontal wells, where errors can be larger.

Magnetic interference

Magnetic interference may be defined as corruption of the geomagnetic field by a magnetic field from an external source. This can cause serious errors in measuring hole direction (azimuth). Potential sources of magnetic interference include:

- Drill strings
- Adjacent wells
- Casing shoes
- Magnetic formations
- Drill collars (e.g., nonmagnetic “hot spots”)

Although all previous error sources may compromise a magnetic survey’s quality, drill-string (axial) interference is probably the most common cause of errors when measuring hole direction. This is because drill strings act as a steel-bar dipole magnet. A typical approach for magnetic survey tools is to place the survey sensor within a sufficient quantity of nonmagnetic drill collars in the bottom-hole assembly (BHA). Magnetic interference diminishes proportionally with the inverse of the square of the distance from the magnetic-field source. The bar-dipole-magnet analogy is simplistic, and there is evidence that downhole drill-string magnetism is more complex, even dynamic in nature. In practice, it can be difficult to completely remove magnetic interference. The magnitude of the effect depends on the strength of the interference field, the inclination and direction of the borehole, and the borehole’s geographical latitude. Highly deviated wells drilled in an east-west direction are likely to suffer greater magnetic-interference errors, especially at higher latitudes (Cheatham, Shih, Churchwell, Woody, & Rdney, 1992; Russell & Roesler, 1985).

There are several techniques to correct the effects of magnetic interference. Most are proprietary, but at least two are based upon a common hypothesis. The corrupted sensor measurements can be replaced with values calculated from a model of the local geomagnetic parameters, which allows azimuth estimation without interference errors. Such techniques have shown to be sound, in theory. In practice, many geomagnetic models are imperfect and result in potentially significant errors in the calculated azimuth. On the other hand, if good geomagnetic-field information is available, such correction routines can provide accurate azimuth data. In some cases, the hole direction’s (azimuth’s) accuracy has approached gyro quality (Russell, Shiells, & Kerridge, 1995).

Cross-axial magnetic interference

This can arise from magnetic “hot spots” or from close proximity to magnetic elements in the drill string. Cross-axial magnetic interference can cause substantial survey errors, especially when the borehole being surveyed trends east-west or is approximately horizontal. Methods have been devised for dealing with this type of interference, including the use of an axial-interference correction. These techniques also rely on

knowing the magnitude of the local magnetic field and dip angle. As with interference corrections noted above, performance can be affected by imperfections in geomagnetic models.

Borehole position error

The largest survey errors are most commonly azimuthal rather than inclinational, and instrument errors are best represented by a two-dimensional error ellipse that quantifies effects of instrument errors on bottom-hole location (Walstrom, Brown, & Harvey, 1969). The error ellipse is expressed as an ellipsoid with the long axis at right angles to the borehole direction and assumes (most) survey errors are random. However, the currently accepted method of computing borehole uncertainty accounts for most survey errors being systematic rather than random (Wolff & de Wardt, 1981). The Industry Steering Committee on Borehole Survey Accuracy (ISCWSA) has compiled a bibliography of publications addressing position uncertainty in borehole surveys.³³

³³ <http://www.iscwsa.net/download/99540d45-a59c-11e6-98be-a5d2ff454e88/>

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