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Autonomous 3D Electrical Resistivity Tomography Monitoring for Geologic Repository Safeguards

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ABSTRACT

A recent geophysical monitoring technique called Autonomous 3D Electrical Resistivity Tomography (ERT) is available that would be analogous to taking repeated magnetic resonance images (MRI) of a geologic repository. This could be used to continuously monitor for indications of diversion or undeclared access. The technique involves placing electrodes within the repository to autonomously and continuously monitor the 3D electrical conductivity of each region of interest. Electrical conductivity can be used as a proxy indicator to assess the state of the materials over time. Systems using the new technology have been successfully deployed to monitor, for example, the movement of chemicals through the subsurface, alterations in electrical conductivity from underground explosions, leaks from buried piping systems at nuclear power plants, engineered subsurface desiccation, and groundwater migration through the subsurface. Finland and Sweden are preparing deep geological repositories for the permanent disposition of spent nuclear fuel. Repositories pose a significant challenge to verification due to the inability to access the material following emplacement and the very long timeframes involved. There is an opportunity to contribute to the overall effort of geological repository safeguards by providing performance details about 3D ERT monitoring that is expected to be cost effective and robust over time. This paper and presentation will describe the modeling work that has been performed to date on various options for deploying 3D ERT in a repository and the costs and benefits of such a system.

INTRODUCTION

Deep geologic repositories for the permanent disposition of spent nuclear fuel pose a significant monitoring challenge due to the inability to access material following emplacement and the very long timeframes involved. A geophysical analysis technique herein called Autonomous 3D Electrical Resistivity Tomography (ERT) has been developed that offers an opportunity to remotely image these repositories. Sensors are emplaced that can continuously monitor for changes occurring in near-real time, and this could be used to detect where anomalous conditions are present, and how they are evolving. Recently, systems using Autonomous 3D ERT have been successfully deployed to monitor subsurface changes in a variety of environments. Some examples are the movement of chemicals through the subsurface [1], alterations in electrical conductivity from underground explosions [2], stress variations in crystalline rock during high pressure injections [3], engineered subsurface desiccation [4], and groundwater migration through the subsurface[5]. Given the range of applicability of Autonomous 3D ERT, there is an opportunity to contribute to the overall effort of geological repository safeguards by providing cost effective performance information over time.

While the application of Autonomous 3D ERT monitoring is relatively new, static ERT is a mature and robust imaging technology. Static ERT is one of the most widely used geophysical techniques, in part because the measured electrical properties are well correlated to pore fluid properties (e.g. salinity, saturation) and lithology (e.g. porosity, mineral composition) [6]. In addition, the measurements are highly scalable depending on the spacing of sensors. Static ERT imaging exposes spatial contrasts in subsurface electrical properties and has been used for identification of weakness zones in crystalline bedrock [7], identification of geologic structures [8] and delineation of high conductivity contaminant plumes [9, 10]. In contrast to static ERT imaging, measurements for time-lapse ERT monitoring are collected over time and the analysis exposes changes from a known background state. This provides a major benefit when interpreting ERT images because the effects of static electrical structure for a given system are subtracted out, enabling the images to focus on temporal changes in a system [11] that would otherwise be obscured. ERT monitoring has been used in numerous applications to image contaminant migration and solute transport [12-14] and has been suggested as a potential tool to detect new, undeclared tunnels within a nuclear repository [15].

The Finnish geological repository, Onkalo is expected to begin operation in 2023, and the Swedish repository at Forsmark will start to accept material about 10 years later. A recent study [15] comprehensively reviewed geophysical methods, including ERT, to detect undeclared activities at a geological repository site. Specifically, static ERT has been used at Onkalo as a geologic and structural characterization tool. While there are many examples available, perhaps the most relevant to this work was performed in Ref. [16]. There, the authors performed cross tunnel ERT imaging at the Onkalo Demonstration Area between pilot holes with 1 m electrode spacing and interpreted electrically conductive regions as deformation zones or fractures. Reference [16] also collected ERT data using electrodes on the floor of a demonstration tunnel that contained several shallow 8 m drillholes. The study found ERT to be a useful characterization tool and proposed that ERT could be used prior to positioning of shallow drillholes for characterization purposes. Reference [15] acknowledged that monitoring would likely require ‘following changes in baseline properties’ and comparing these changes to declared activities. Static ERT was mostly evaluated as a method to provide independent verification and characterization during construction, with recommendations of post closure monitoring from the surface. ERT monitoring was suggested as a useful application technique but not investigated in previous studies.

The goal of this work is to determine the feasibility of Autonomous 3D ERT for monitoring geological repository installations with a focus on safeguards. Using ERT as a long-term monitoring tool is relatively new and its capabilities have not been previously considered, even by recent reports. Within a geologic repository, changes in bulk electrical conductivity can be used as a proxy metric to monitor for changes in material properties or structural integrity Precisely, implementation of Autonomous 3D ERT would allow an operator to temporally identify the location and magnitude (i.e., impact) of an unexpected anomaly or undeclared activity within the repository.

This feasibility study uses site-specific information based on the Onkalo repository to determine if Autonomous 3D ERT could provide the resolution necessary for independent verification of the repository structure and/or observe any deviations to plans during spent nuclear fuel disposition. This study also determines if sensors could be left in place to monitor changes over longer periods of time.

ONKALO

Facility Description

Onkalo is being constructed on the island of Olkiluoto in Finland. Details on the design can be found in [17]. The deep geological repository for Finnish spent nuclear fuel will be located at a depth of 400 to 450 meters in solid rock that is a mixture of granite and gneiss. Access tunnels will lead to up to 350 m long deposition tunnels. The work presented here has assumed that the KBS-3V [18] method for storing the spent fuel will be used. KBS-3V was developed by Sweden and places multiple spent fuel assemblies in large, sealed copper canisters. These copper canisters are then placed in vertical deposition holes (representing the V in KBS-3V) that are drilled into the floor of the deposition tunnels. A diagram of the planned deposition tunnels and deposition holes is shown in Figure 1. The tunnels are spaced 25 m apart. Each deposition hole will be 6 to 11 m apart depending on the thermal properties of the spent fuel being deposited. The deposition holes will be no closer than 32.5 m from the tunnel entrance and 4 m from the tunnel end.

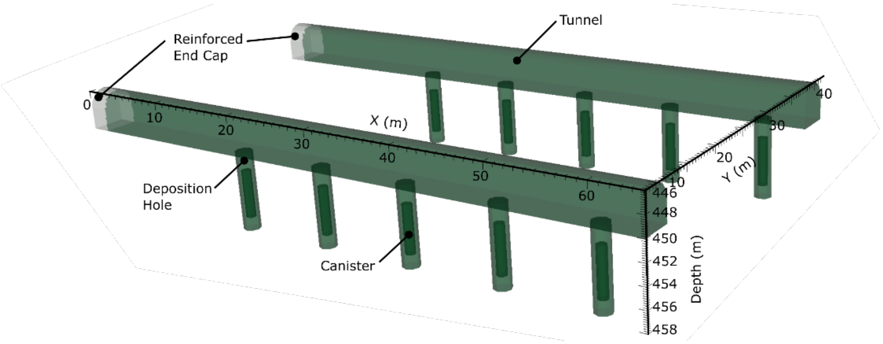

Figure 1. A 3D diagram of two adjacent deposition tunnels with deposition holes drilled in the floor. Each deposition hole contains one spent fuel storage container.

After the spent fuel storage containers are placed in the deposition hole, the holes are filled with clay. Then, the deposition tunnel is prepared and backfilled with more clay. The clay will absorb water naturally present in the repository and swell and limit any movement of material as well as provide radiation shielding. The end of each deposition tunnel will be sealed with a concrete end plug. There is a plan for a complex sequence of temporary gates to limit unauthorized access to the various parts of the repository as it is being filled.

ERT

Autonomous 3D ERT uses E4D [19], an open-source geophysical modeling and inversion software designed to address the computational demands of inverting large-scale time-lapse 3D data sets by running on distributed memory parallel, high-performance computing systems. Real-time 3D monitoring capabilities enabled by E4D were recognized with an R&D 100 award in 2016. E4D also has unique capabilities for simulating the effects of metallic infrastructure (i.e., metal canisters, rebar, etc.), which is important for this work.

SAGOR {IAEA, 1998 #31}and ASTOR {International Atomic Energy Agency, 2018 #32} were previous large efforts examining the challenges related to the long-term storage of spent nuclear fuels. Their reports had considered ERT as a static characterization tool but not for safeguards monitoring. As mentioned in the introduction, ERT has been used at Onkalo in the last seven years [16] for static cross borehole imaging and imaging of experiment deposition holes.

ERT Simulation Results

The main challenge of this effort is how best to apply autonomous 3D ERT to safeguards. The first consideration was inspired by surface seismic techniques: surround the entire site with boreholes instrumented with electrodes. There were two immediate problems with that approach: 1) Even with good backfilling of the boreholes, they could threaten the integrity of the repository by providing a pathway for water to enter or for waste to exit. 2) The position and change sensitivity inside the repository would not be very good with electrodes that far away. Like with other imaging techniques, distance from the object to be imaged plays a large role in determining image resolution.

To get the electrodes closer to the spent fuel, the existing tunnel infrastructure could be used and instrumented with different electrode densities and layouts. For the ERT modeling, the material properties of the repository (rock, clay, copper) were assumed to be the values given in the literature. In reality, the values for the materials could differ but representative values were used.

Deposition hole build out

The first scenario examined was where the deposition holes have been drilled and then are filled with canisters and clay one by one. The results, shown in Figure 2, were simulated using 1 m electrode spacing on edge of the floor of the deposition tunnel. The left side of Figure 2 shows the sequence of filling each deposition hole where the time-lapse ERT inversion calculation is performed without any assumptions about where the source of changes could be limited to. However, if it is assumed that changes could only occur in the known locations of the deposition holes, then the inversion converges on a much clearer solution as each deposition hole is filled.

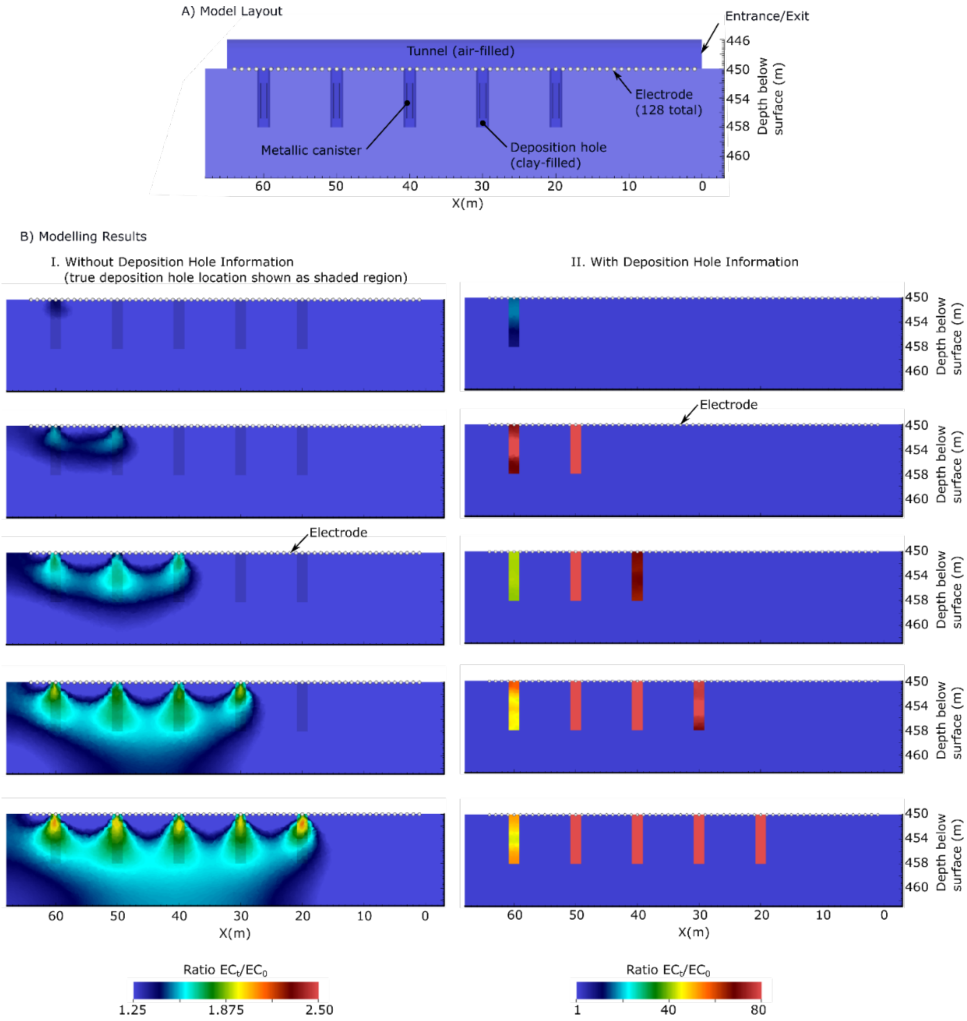

Figure 2. Deposition hole build-out ERT images for 1 m electrode spacing on the edge of the tunnel floor. Modeling results in B) show the true location of the deposition holes as shaded regions for reference and these locations were I) and were not II) provided as information to the ERT inversion.

A similar set of plots was generated as the deposition tunnel is backfilled. The solution was able to observe the deposition tunnel as it was filled up with clay (not shown).

Tunnel Monitoring

The next study examined what would happen if conductive and resistive anomalies were introduced in the vicinity of the deposition tunnel post closure. Figure 3 shows that small changes near the tunnel would be easily observed using 1 m electrode spacing after the tunnel has been filled with clay and sealed.

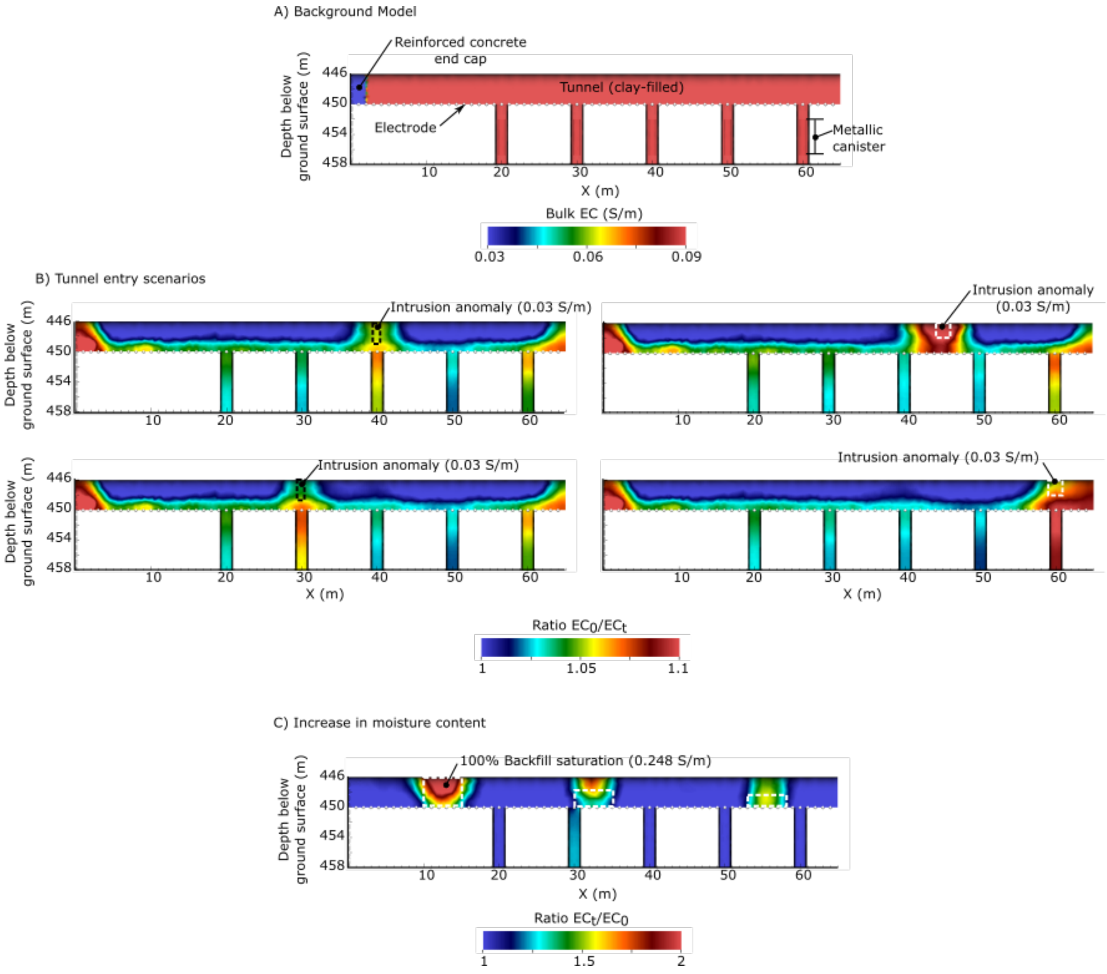

Figure 3. Time-lapse ERT images from A) background model for B) tunnel entry scenarios and c) increases in moisture content from an initially unsaturated state.

Deposition Hole Monitoring

Next, options for better imaging of the deposition holes were examined. Figure 4 shows the results of placing 16 electrodes into the deposition hole itself with 8 on one side and 8 on the other with 1 m spacing. As would be expected, having electrodes near the storage canister improves imaging resolution. The top part of Figure 4 shows the locations and shapes of various resistive (left) and conductive (right) anomalies. As the bottom part of Figure 4 shows, those changes were easily observable using 4D ERT. Additional studies were performed using fewer electrodes in the deposition holes and the ability to image was lost. However, changes in raw data were still observable that would give an indication of the timing and location of unexpected changes to the material properties in the deposition hole.

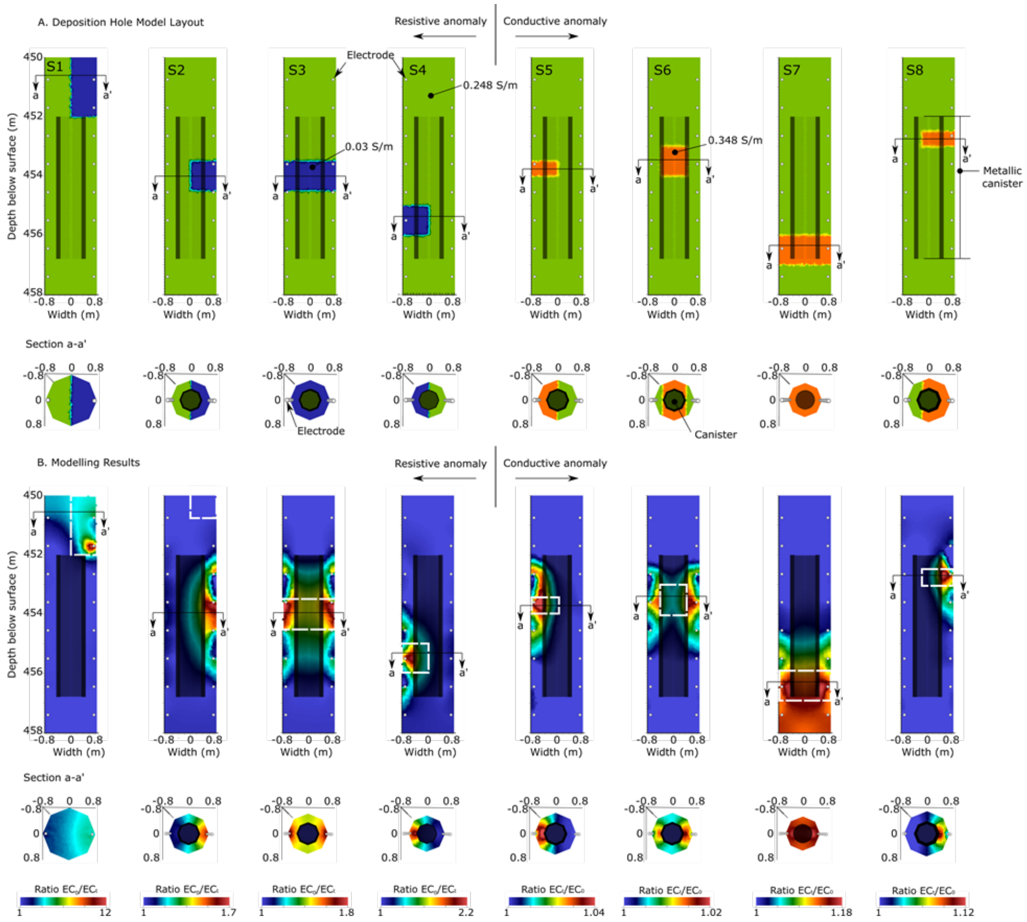

Figure 4. Time-lapse ERT monitoring for 16 electrodes emplaced with the deposition holes for resistive and conductive anomalies. The true models are shown in A) and the resulting ERT images are shown in B). White dashed boxes shown in B) depict the actual location of the anomaly shown in the corresponding image in A). Canisters are shown as transparent in A). Shaded regions in B) indicate the location of the canister.

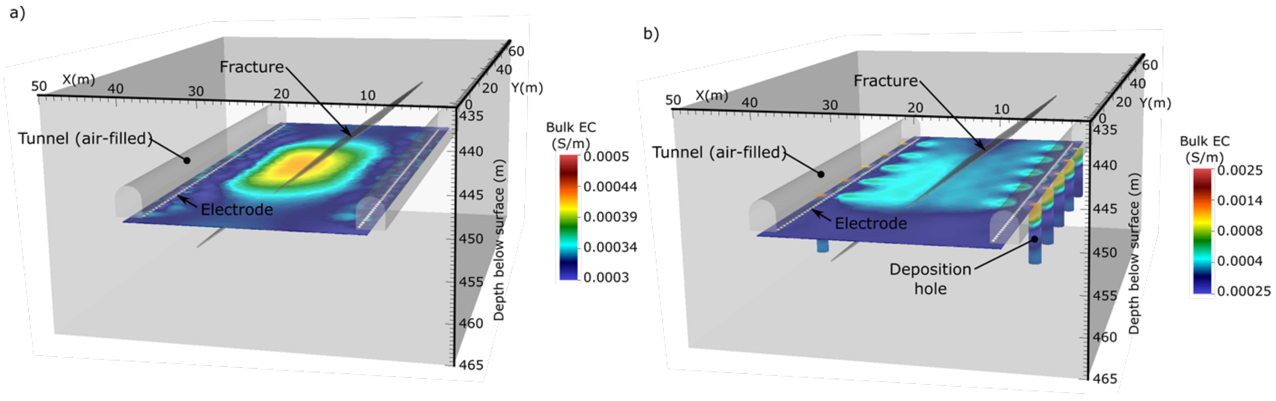

Figure 5. Cross tunnel static ERT characterization between two air-filled adjacent tunnels. Shown are ERT images a) with the presence of deposition holes and b) without.

Additional application of 3D ERT

An additional application of 3D ERT is closer to the traditional usage. If there are two adjacent air-filled tunnels that are instrumented with electrodes, cross tunnel imaging is possible. The top part of Figure 5 shows an example of the detection and localization of a fracture between the two tunnels. However, the lower part of Figure 5 shows that this capability is significantly lessened when the deposition holes are present and filled with the canisters and clay. This is due to the high conductivity of the canisters and clay relative to the rock.

COSTS, LONGEVITY, FEASIBILITY

ERT systems consist of electrodes connected to insulated copper cables and survey instrumentation to conduct the measurements. The electrodes are typically made of metallic rods 20-30 cm long and 1-2 cm in diameter that are hammered into a pilot hole within the rock. Each survey system can be connected to up to 16,384 electrodes. With the exception of labor costs for installation, the all-inclusive ERT system cost per electrode typically ranges from \$500 to \$700 USD, and electrodes typically come in groups of 64. For a 300 m long tunnel (similar to Figure 2 but longer), 5x64=320 electrodes would be needed assuming one electrode per meter. That would cost between \$164K and \$224K USD. The cost to instrument four deposition holes with 16 electrodes per hole (see Figure 4) would be between \$32K and \$45K USD.

Long-term survivability of an ERT monitoring system is determined by the components of the system that cannot be replaced or maintained, namely the buried cables and electrodes. A primary advantage of ERT monitoring is that cables and electrodes have no moving parts and can be custom designed for long-term survivability in a given setting. For example, geochemical conditions at Onkalo are such that the copper waste cannisters are anticipated to maintain viability for many thousands of years. Similar longevity can be expected for electrode takeouts and electrodes if they are also made of copper. In that case, the longevity of the monitoring system is reduced to the longevity of the waterproofing and insulating jacketing of the electrode cables. Literature values for the design lifetime of underground cables range from about 20 to over 50 years depending on conditions and current load of the cable [20]. With the currents and usage of the cables expected to be low, longer lifetimes would be expected.

While traditional ERT has already been used at Onkalo, ERT for safeguards would require different emplacement of the cables and would be in the deposition tunnels. The latest design calls for a concrete tunnel floor to be installed on top of gravel along with a wire mesh and shotcrete on the walls for personnel safety. If the ERT electrodes could be installed under the concrete floor, they would not be expected to impact operations. However, the wire mesh on the tunnel walls would be expected to reduce the resolution of tunnel electrodes but not those in the deposition holes. The literature also mentions the potential removal of the shotcrete and wire mesh during backfilling which would restore the resolution of the tunnel electrodes.

CONCLUSIONS

ERT was evaluated as a technology to provide 1) geologic information in between deposition tunnels; 2) independent verification of the emplacement of spent nuclear canisters during the construction phase and 3) long-term monitoring of deposition tunnels and canisters. Two controlling factors in these evaluations were the conductivity contrast between the buffer material and the intrusion anomaly and the high conductivity of the buffer material which controls the current pathways and the penetration depth. Generally, a higher conductivity contrast allows for a higher probability of ERT detection where contrasts could be caused by natural phenomena (i.e., swelling of buffer material) or an undeclared disturbance or physical entry. ERT produces images of bulk electrical conductivity which is dependent on moisture content, porosity, temperature, and lithology. Note that these physical properties cannot be differentiated in ERT images without other site information.

It was shown that air-filled cross tunnel ERT imaging for geologic information can be useful for detecting a high conductivity fracture zone. Cross tunnel ERT was limited to where two adjacent tunnels were air-filled and void of any deposition canisters. Conductive materials such as the buffer material and the copper canisters create a less-resistive pathway for current to flow limiting the ability of ERT to image between adjacent tunnels.

While not a substitute for other forms of verification such as cameras, ERT imaging can provide another line of sight to construction/build-out. ERT datasets collected after buffer material or canisters have been added to the tunnel and deposition holes have large decreases in transfer resistance compared to an initial dataset without these materials. This large change in electrical data and including engineering build-out information within the ERT modeling allowed ERT imaging to ‘see’ the deposition hole build-out and the tunnel backfilling.

For the longer-term monitoring, the tunnel and deposition holes are backfilled with buffer material which has a high conductivity, and electrodes are embedded within the buffer material. While this allows for current to flow preferentially within the boundaries of this high conductivity material, a sensitivity analysis showed that the measurement sensitivities remain close to the electrodes. This had implications for all the longer-term monitoring evaluations. For example, tunnel monitoring with 1 m spaced electrodes on the tunnel floor could detect anomalous features (in all cases) however the dimension, contrast and positioning of the anomaly determined how well this could be seen in the ERT image. This study purposefully decreased dimensions and positioned anomalies such that this could be evaluated. With tunnel monitoring, larger changes in conductivity contrast and dimension would be reliably detected, while smaller changes (< 1 m^3 combined with less than one order of conductivity magnitude change) might be challenging. Tunnel floor electrodes (1 m spaced) did not reliably detect long-term changes within the deposition holes, however the emplacement of electrodes directly within the deposition holes did.

The emplacement of electrodes within the deposition holes alongside the canisters showed it was possible to detect changes in conductivity due to natural or unnatural causes. Using 16-electrodes allowed for ERT images to be generated which pinpointed a more precise location of the anomalous feature.

The costs, longevity, and feasibility were also examined. The ERT electrodes could provide an affordable, long-term monitoring option that would give greater insight into the activities during the construction, filling, sealing, and storage phases of the repository.

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