

# Autonomous Inspection of Geologic Repositories

Current State of the Art and Future  
Directions

September 2020

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## Abstract

Geological repositories for nuclear waste, including spent nuclear fuel, present a significant challenge for traditional International Atomic Energy Agency (IAEA) safeguards tools due to their inaccessibility and demanding operational conditions. The IAEA has been working closely with Member State organizations currently involved in repository construction and planning, including Euratom, the Finnish and Swedish regulatory authorities, and relevant facility operators. However, the verification challenge remains unsolved, and there persists an out-standing need for tools and approaches that will help the IAEA verify that no nuclear material is diverted from a repository environment. The challenge is also not static. Activities must encompass verification of the design, prior to and during the construction/operation phase, and post backfill. Throughout these various phases, it is imperative that the IAEA maintains a continuity of knowledge (CoK) of all material including information on material inventory and flow. This paper highlights these challenges and outlines how they might be addressed by using remote or autonomous vehicles. Specifically, we discuss the current state of the art in robotic autonomy for known or partially known environment mapping and patrolling, as well as shared autonomy, where humans collaborate with closed loop automation to complete tasks. We explore the feasibility of using rovers for these verification tasks, along with the challenges associated with system implementation. Hardware and software suggestions are provided based on the adoption of similar technologies in other comparable areas and ability to close technical gaps. Lastly, human-robotic interactions are considered based on the challenges of the environment of the repository and effective deployment and continued operation of the robot system.

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## 1 Introduction

IAEA inspection resources will become increasingly taxed as more nuclear waste repositories become operational. This paper explores possible robotic technologies to aid and augment IAEA inspection of nuclear geological repositories. Specifically, the recommended technologies can help maintain continuity of knowledge (CoK) of nuclear materials during the repository's operation phase. Due to its magnitude, a nuclear repository will transition through several phases: pre-operation, operation phase, and post-operation. The pre-operation phase involves geological assessment of a nuclear waste repository site. The operation phase, the focus of this paper's technology recommendations, is the most complex and involves the construction, processing, emplacement, and backfill of nuclear wastes. The post-operation phase addresses closure of the facility and the long-term storage and handling of nuclear waste.

The variability of possible geological waste repository designs and the uncertainty of long-term technology development drives a focus on technologies to aid the inspection during the operation phase. Furthermore, each country may have their own variant of a nuclear geological waste repository and designs in various stages of development. For instance, the KBS-3 repository is currently being developed and used by Sweden and Finland [1]. The KBS-3 method developed by SKB provides a model template for the technological recommendations and the applicability of this approach is not limited to the KBS-3 repository design.

During the operation phase, the nuclear waste repository consists of a surface facility (above-ground) and a sub-surface facility (below-ground). The surface facility can serve a variety of functions including simply acting as an entrance to the sub-surface facility or housing a waste encapsulation and cooling plant. Due to the accessibility by IAEA inspectors to the above ground facilities, this paper will not focus on technologies that can help augment and automate above-ground inspection processes. However, the recommended technologies may certainly still apply to above-ground inspection processes. In contrast, sub-surface facilities have many limitations that prevent easy IAEA inspection. For example, certain tunneling activities will be ongoing concurrent with nuclear waste emplacement and possible backfilling.

## 2 IAEA Safeguard Objectives

IAEA safeguard measures and approaches for the back end of the nuclear fuel cycle have matured over the last several decades. However, verification methods for final disposition of spent fuel in underground repositories are just now being formalized, as the first underground repository is nearing completion. The IAEA considers the spent fuel disposed in the geological repository to be inherently retrievable and subject to safeguards for as long as the safeguards agreement remains in force. To help prevent and detect such diversion, several safeguard criteria for the final disposal of nuclear waste in geological repositories have been identified [2, 3, 4], including:

1. Design Information Verification (DIV)
  - (a) Verify the declared repository design information such as declared equipment and mechanical, piping, instrument, and architectural blueprints
  - (b) Detect undeclared exhuming activities inside or surrounding the repository
2. Continuity of Knowledge (CoK)
  - (a) Detect tampering of any container with nuclear material, including shipping casks or waste canisters
  - (b) Detect the removal of material from any container, cask, or canister.
3. Material Accountancy
  - (a) Verify receipt, continued presence, and declared (or undeclared) transfers of nuclear materials and waste canisters

- (b) Detect replacement or removal of material at the gross defect and partial or bias defect level

A typical deep geological repository will have many tunnels and drifts well below the ground. Once the canister emplacement operation is complete inside a deposition tunnel, that deposition tunnel will be backfilled and closed. Therefore, at any instant in time, a repository may have a backfilled tunnel, a tunnel in which an emplacement operation is underway, and an empty tunnel. This variability and the inaccessibility of the repository system will pose challenges for implementation of DIV, containment and surveillance (C/S), and material accountancy via non-destructive assay systems. This paper suggests different robot operation modes (e.g., full or shared autonomy) and approaches to aid in achieving the IAEA repository safeguards criteria outlined above. Specifically, the case of the KBS-3 sub-surface canister system is considered, however, the technology could apply much more broadly to other repository systems.

The above-ground operational aspects are not addressed here due to the ease of accessibility by the IAEA inspectors and applicability of traditional safeguard methodologies. The material accountancy assurances are not addressed here since material verification (“assay”) cannot be performed within the repository [5]. The encapsulation plant, which may be part of the surface facility of the repository, presents the last opportunity for nuclear material accountancy. Furthermore, the focus is on operations conducted sub-surface at the repository and assumes that all the relevant information from above-ground operations is passed down to the underground section for consistent CoK of the material. The following sub-sections delve more deeply into each of the safeguard requirements and the assurances required in the underground portion of the repository. These assurances and requirements are not exhaustive and additional assurances may be required by IAEA safeguard agreements with the host country of the facility’s operation.

### 2.0.1 DIV Assurances

DIV will be essential for safeguarding underground repositories [4, 6, 5]. The early 1990’s Program for Development of Safeguards for the Final Disposal of Spent Fuel in Geological Repositories (SAGOR) [6], describe the DIV process as separated into informal and formal activities. The informal DIV activities begin after the basic facility designs are submitted to the regulatory authorities. Information such as plant parameters, plant layout, process description, and nuclear material accountancy can be historically archived for future comparison. The formal DIV activities begin after completion of facility construction and before facility operations begin. These formal activities aim to categorize all aspects relevant to safeguards, prioritize the performance of verification activities, and ensure that all design changes are verified [6]. Due to its importance, the DIV of the repository is a focus of this paper. According to Fritzell [6], the DIV must provide the assurance that:

1. Design information of repository with access routes and other features are verified
2. Backfill of emplacement tunnels are completed as declared with no voids or other means (e.g., softer fill material)
3. Sealing of back-filled areas are completed as declared
4. Integrity of repository sealed areas has been maintained through construction phase
5. During the final stages of operational life of the repository, access routes to back-filled areas are filled
6. Decommissioning is completed as declared with removal of all surface equipment and facilities
7. No undeclared excavations or boreholes around the repository within a given distance, with none that are active during operation or after the sealing

### 2.0.2 C/S Requirements



Containment and surveillance of nuclear material and waste is an integral part of safeguard approaches with many different options for monitoring systems in non-underground settings. It is accepted that if all diversion pathways are fully addressed via monitoring, the continuity of knowledge can be considered maintained. Several C/S approaches have been recommended for spent fuel by the US Nuclear Regulatory Commission and includes digital camera surveillance, different seals (e.g., E-type, bolt, Vacoss, weld), radiation monitoring, weight pads, and other unique identifiers [6]. However, for underground C/S, most of the traditional containment and surveillance methods involve monitoring egress points due to the inability to access the containment unit after emplacement and can be used to support DIV processes. A list of C/S system requirements are derived from Fritzell [6] and Mongiello et al. [5]:

1. Ensure continuity of knowledge from above ground activities
2. Systems are designed for independent operation and remote monitoring
3. Redundancy (e.g., Dual C/S) within the C/S system is employed
4. Coverage of all credible diversion paths
5. Ability to report health status to safeguard authorities
6. Devices should be tamper-resistant and be capable of indicating tampering has occurred
7. Devices should have low “false alarm” frequencies

### 3 Operation Phase

A typical KBS-3 repository system during operation phase consists of underground openings, nuclear waste canisters, buffers, backfill, and engineered barriers as seen in Figure 1. According to the KBS-3 production report, construction of additional drifts in the underground sections can occur concurrently with the operation phase of the nuclear waste facility [1]. A brief summary of the construction process is provided here to highlight the applicability of the suggested automation technology. More detailed information is contained in KBS-3 reports [7, 8].

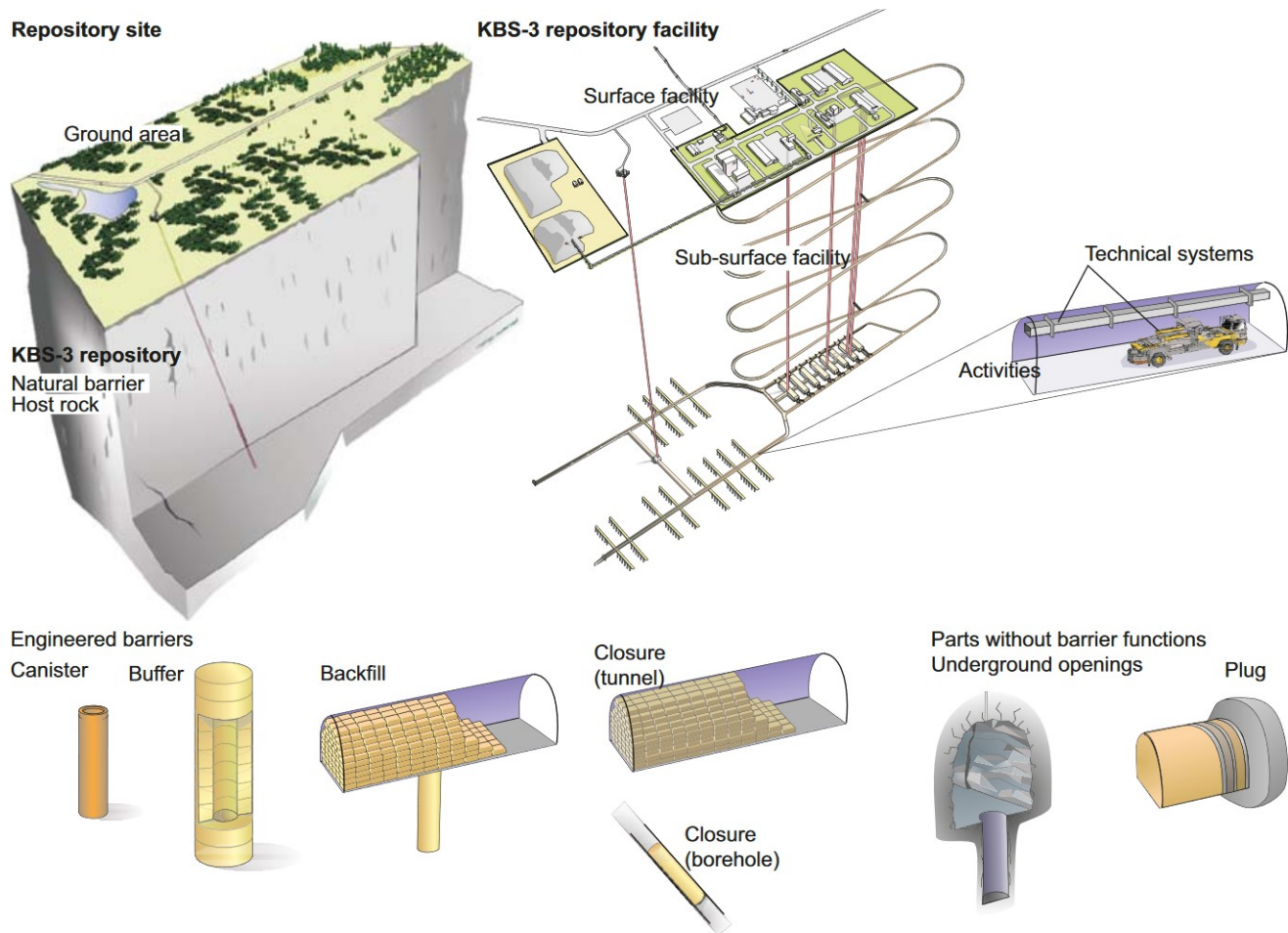


Figure 1: KBS-3 repository layout [1]

### 3.1 Spent Fuel Canister

One representative spent fuel canister design, the KBS-3, involves a corrosion-resistant copper shell that encapsulates the spent nuclear fuel assemblies. The copper shell is designed to properly attenuate the radiation, to withstand mechanical and corrosion load, and to accommodate multiple fuel assemblies. However, safety considerations related to the long-term storage of the waste canister inside the repository limits the maximum decay power and radioactivity at the canister's surface and, subsequently, the number of fuel assemblies that can be included inside a canister. The burn-up data and age of the spent fuel assembly are required to determine the radioactivity and the decay heat of the fuel assembly. The KBS-3 canister has specific guidelines for the acceptable decay power and radioactivity at the canister surface, such as:

1. Maximum permissible decay power: The KBS-3 safety guidelines explicitly state that the total decay power in each canister should not exceed 1,700W. This limitation should maintain the temperature in the buffer less than 100°C. Temperatures exceeding this value may have adverse impacts on the properties of the engineered barriers and the rocks.
2. Radiation dose rate: Similarly, the radiation dose rate at the surface of the canister needs to be less than 1Gy/h. High radiation levels at the canister may lead to the formation of nitric acid and other corrosive species at the canister surface [9].

The canister is deemed ready to be emplaced in the repository once these safety conditions are met.

## 3.2 Buffer Installation

According to the KBS-3 process [1], when the canister is ready to be emplaced, a buffer of bentonite clay is installed around all its sides. First, the buffer bottom block and ring-shaped blocks are installed. After the deposition of the canister, a buffer block is placed above the canister and caps the deposition hole. The buffer of bentonite clay serves gives stability to the canister and provides protection from underground water to reach the canister surface. This buffer block may serve as a temporary cap if the repository is eventually backfilled. A flow diagram of the buffer installation process is shown below in Figure 2,

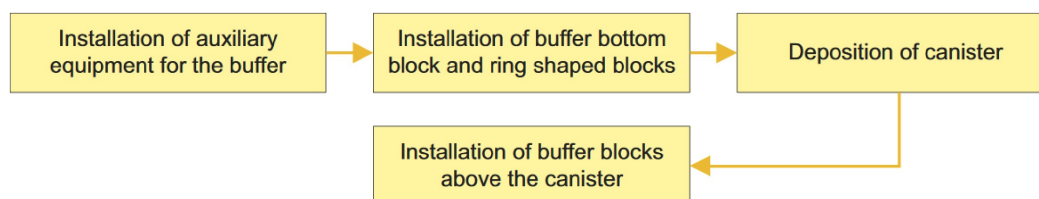


Figure 2: Buffer installation sequence [1]

## 3.3 Backfill Installation

In the KBS-3 repository designs [1], backfilling occurs after the buffer installation are finished. The backfill procedure begins with the removal of the protective buffer block capping the waste canister and includes the installation of buffer pellets. This step represents the last opportunity for direct inspection techniques such as visual inspection. Afterwards, various backfill installation steps are conducted. Backfilling ends with the installation of the plug. The plug serves as a barrier between the backfill over the deposition holes and the main tunnels. These plugs will be exposed until the backfill process for the tunnel section and as such, the plugs will serve as a focus of inspection to maintain CoK. The complete KBS-3 backfill diagram is outlined in Figure 3.

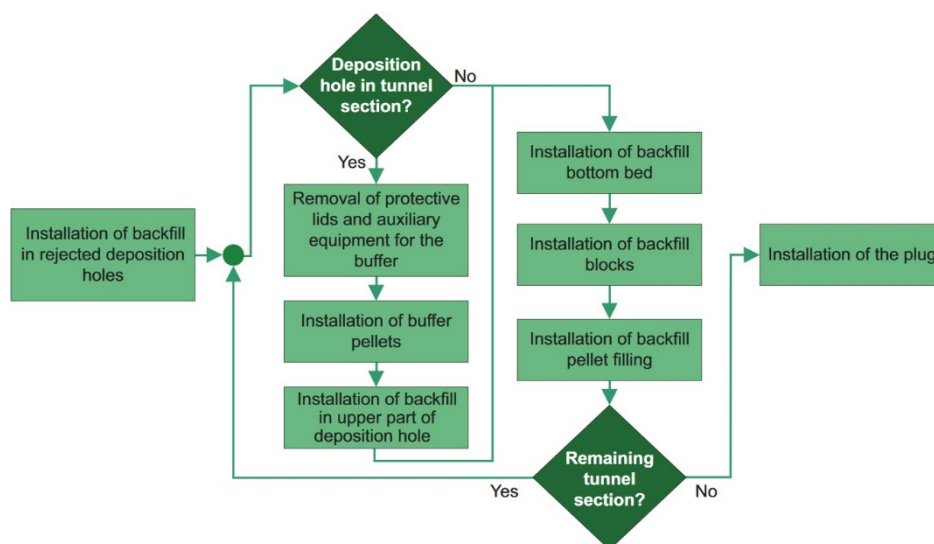


Figure 3: Backfill installation process [1]

## 4 Autonomous Verification of Geologic Repositories

This section addresses different robotic technologies which can be employed by IAEA inspectors to maintain continuity of knowledge of nuclear waste in geological repositories. Robotics has been utilized in environments that are similar to underground nuclear waste repositories with goals such as inspection, search and rescue, and exploration [10]. Furthermore, there is active development and government funded projects in progressing the capabilities of autonomous robotics [11]. The technological recommendations are focused on the sub-surface aspects of the operation phase. Each technology recommendation will include general information for practical implementation and current research direction. The autonomous approach section is divided into two subsections. The first section lists the different technologies which can be employed on the robot rover in order to enable IAEA safeguards criteria. These technologies are suggested to be implemented regardless of the level of automation. The second section describes the different levels of automation of inspection implementation. This second section describes the advantages, disadvantages, and considerations for the state-of-the-art automation implementations.

### 4.1 Robot Sensing Technologies

The verification technologies recommended for implementation on rovers require general considerations of portability, power consumption, current state-of-the-art, and the ability to augment IAEA inspection. The verification technologies are targeted towards implicit and indirect inspection techniques to maintain the CoK since most of the sub-surface portion of the operation phase does not involve direct visual line-of-sight with the nuclear waste canisters. Additionally, specific implementation details which are dependent on different geological waste repository designs are not discussed in this paper.

#### 4.1.1 LiDAR Mapping

Large-scale mapping of complex environments has been effectively accomplished by long range light detection and ranging (LiDAR) sensors and point cloud methods for a variety of uses. Specifically, LiDAR has been applied in underground mine environments like the proposed nuclear geological waste repositories [12]. Furthermore, airborne LiDAR technology has been used for seismic deformation morphology studies to ensure the geological properties are suitable for nuclear waste storage [13]. Recently, the Joint Research Centre has employed the use of backpack mounted LiDAR for IAEA usage in nuclear facility design information verifications [14]. The very same technology can be mounted on a mobile robot for Design Information Verification (DIV) of the repository during construction and operation stage. LiDAR technology, combined with odometry information, can create detailed digital maps which can be compared to reference facility designs during each routine inspection, addressing the IAEA DIV safeguards criteria.



Figure 4: Velodyne LiDAR Puck [15]

LiDAR hardware is commercially available and widely supported. This sensing technology benefits from a large market and wide variety of applications. There are multiple hardware manufacturers (e.g., Velodyne, Waymo, Sick) who also provide some off-the-shelf software to fuse the data together from different viewpoints. For robotic integration, there may be more specific work necessary to integrate the LiDAR information with odometry information. SLAM algorithms are commonly used in robotic applications to combine the data streams to provide real time maps and floor plans [16].

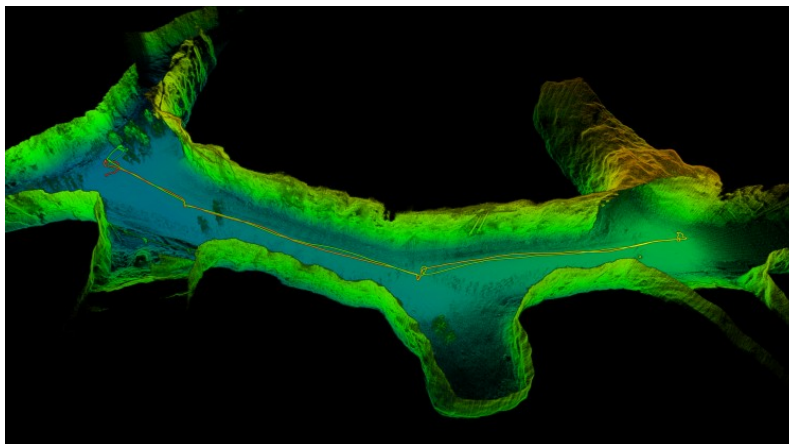


Figure 5: Map created using LiDAR and a robot [17]

#### 4.1.2 Optical Imaging

Alongside long-range perception capabilities like LiDAR, short range feature identifications can also support inspection routines. Optical camera sensors can be an option for short range analysis of defects or disturbances to different components of the geological repositories. These sensors can have a shorter sensing range compared to the LiDAR scanning systems but have increased resolution and optical distinguishing capabilities like RGB. For example, a camera can be used to visually inspect the surface of a plug at the end of a deposition tunnel and compare with historical data to ensure little to no plug deviations or disturbances. Feature-based identification methods are available and image recognition of defects and surface cavities can be conducted. Furthermore, cameras can be used to supplement or augment seal integrity inspections in surface or sub-surface facilities. These potential applications address all three of the containment and surveillance IAEA safeguard requirements through indirect means.



Figure 6: Intel Realsense D435i RGBD Camera [18]

Like LiDAR, imaging technology is readily available and receives support from a variety of industries. A few examples of camera sensor manufacturers are Intel, Sick, and Keyence. Much of the novel implementation for this application would be in software development. While image displaying software can be configured off the shelf with little to no effort, machine vision and recognition software are likely to be required for more intensive inspection tasks. These tasks can include plug inspection, canister seal inspection, and backfill surface disturbance validation. Algorithms like SIFT, SURF, and ORB have been used readily in applications which require image feature



comparisons [19, 20]. These techniques can be used to compare reference images taken at the time of construction completion. In the plug imaging example, these algorithms can be used during each inspection to compare against the images taken at the time of plug installation. Research can be conducted to establish disturbance and deviation thresholds of image matching scores for IAEA safeguard baselines. According to the KBS-3 report on plug designs, the plugs are mostly made from a concrete material [21]. Image vision analysis for concrete damage detection is an active research area [22] and the IAEA itself has considered non-destructive testing techniques for concrete inspection [23]. Camera technology can augment IAEA inspectors, providing additional feature identification capabilities and the necessary visual feedback.

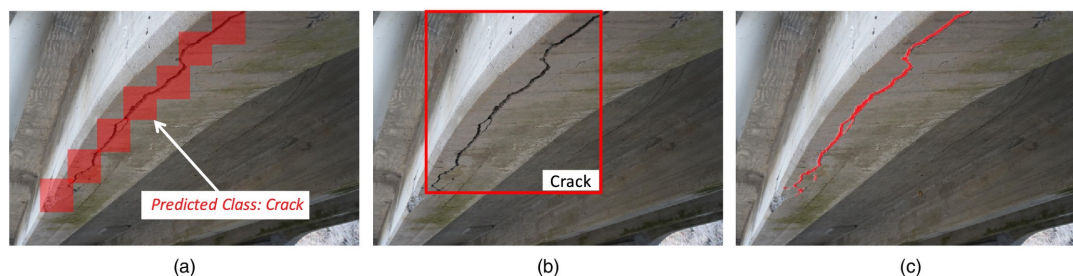


Figure 7: Concrete Flaw Detection using Deep Learning CNNs [24]

### 4.1.3 RFID On Metal Tagging

Traditionally, radio-frequency identification (RFID) tags are commonly used to identify objects uniquely. Tags are attached to an object and are later identified with the help of a reader or interrogator. RFID systems have an integrated circuit and a transponder that communicates to an RFID interrogator through radio waves. However, traditional RFID tags may not be applicable in a subsurface repository since canisters like the KBS-3 are made of copper. The buffer layer may prove to be a barrier for the communication between transponder and the interrogator. A potential solution is a magnetic alternative to RFID, RFID-on-metal, which uses a packet-based wireless technology. For example, RuBee (IEEE 1902.1) is an RFID-on-metal tagging protocol that is accurate even when attached to a metal surface [25]. The wireless signal has been shown to also travel through solid materials [26]. RuBee tag has been shown to work even when embedded inside a steel plate, as shown in figure 8.

Additionally, RuBee comes with a long battery life of more than 15-25 years [27], which supports the long-life operational requirements of KBS-3 better than normal RFID tag [28]. Furthermore, since RuBee communicates at a low frequency of 131KHz and has low power characteristics, it is an attractive technology for operation in harsh places and near or on steel. Specifically, RuBee tag has been tested as a means of sensor communication from within a stainless-steel drum-style radioactive material package [27], as depicted in figure 9.

RuBee's reader/interrogator comprises a base station and an antenna. Furthermore, the integration of an RFID reader suitable for the detection of an RFID tag can be accomplished on a robot system [29]. Therefore, this approach could be used to verify the continued presence or movement of material, particularly before any back-fill stage is initiated. Considering the KBS-3 repository design, for example, uses copper canister to house the spent nuclear fuel, which is, in turn, encapsulated inside cast iron canisters. Since the copper canister acts as a barrier for the spent nuclear fuel from the outside corrosive environment, the RuBee tag could be placed safely outside the cast iron canister or even embedded within. As the RuBee's communication protocol is based on magnetic field waves it may not be susceptible to the negative effects of liquid and metals compared to high frequency radio waves [27]. Therefore, the low frequency and long wavelength characteristic might be suitable for bentonite clay and copper canister spent nuclear fuel encapsulation. A robot system mounted with the reader could be used to identify the unique identity of the RuBee tag placed inside the copper canister, which will further validate the C/S safeguard requirement.

Furthermore, the RuBee tagging system is suitable for the attainment of nuclear safeguards in the underground repository condition due to its long battery life of 15-25 years. Also, it has CPU capability and comes with optional sensors. Therefore, it has a large and unique tagging memory, which would enable the unique identification of the canister.

However, success of the RuBee system for an underground repository may require additional validation in real situations, as there are few experimental results regarding the effectiveness of the RuBee system in a corrosive and/or high radiation environment.

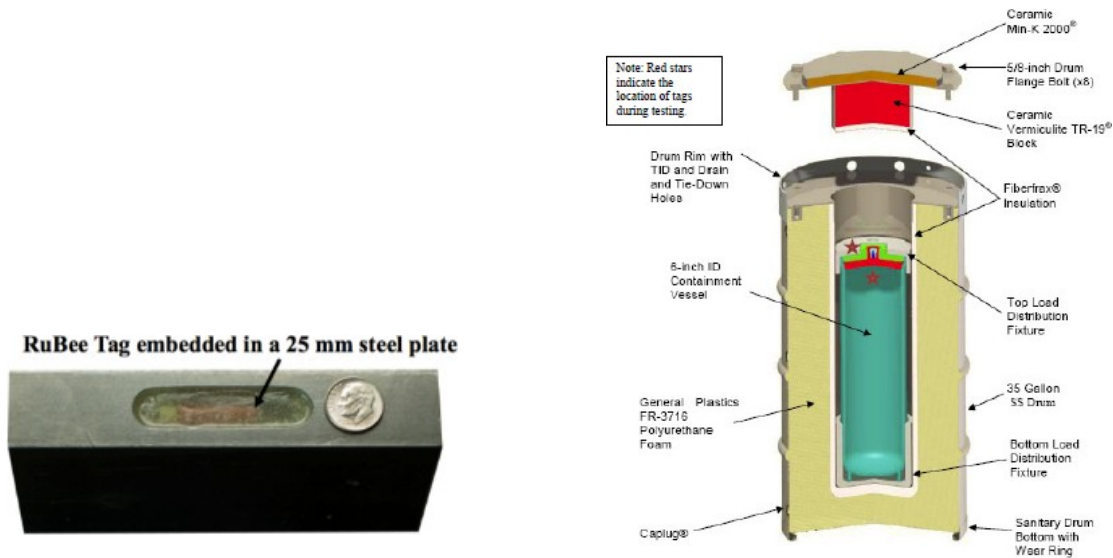


Figure 8: Embedded RuBee Tag inside steel plate

Figure 9: RuBee Tag inside US-DOE certified Type-B Model 9977 drum

#### 4.1.4 Ground Penetrating Radar Systems

Ground-penetrating radar (GPR) is a non-destructive geophysical technique to investigate the underground surface. This method can provide a high resolution 3-D subsurface image using radar pulses in the microwave band of the radio spectrum. For the creation of a subsurface image, a radar pulse is transmitted through the surface material, and the strength and time of reflected signals are recorded. Reflections are produced based on the electrical conduction properties and dielectric permittivity of the material from which reflections occur. Metals act as a complete reflector and thus do not allow any amount of signal to pass through. The frequency of the radar pulse could be optimized to the reflective characteristic of the buffer material. If an area is to be scanned, then a series of pulses will be sent throughout the surface [30]. This subsurface imaging capability of ground-penetrating radars is actively utilized to detect metallic landmines buried inside ground [31]. For the KBS-3 repository design, the spent nuclear fuel waste canister is to be emplaced inside the bentonite buffer. Therefore, GPR technology could be used to verify the continued presence of the waste canister emplaced under the buffer surface due to the electrical conduction properties and dielectric permittivity difference between bentonite clay and copper canister.

The working principle of a GPR system, depicted in figure 10 [32], includes a transmitting antenna to produce short-duration high-power radar pulse of energy to be radiated into the ground. Also, an antenna receives the reflected or back-scattered signal from the object located within the ground. The transmitted and reflected signal is further analyzed based on the speed of light in different materials.

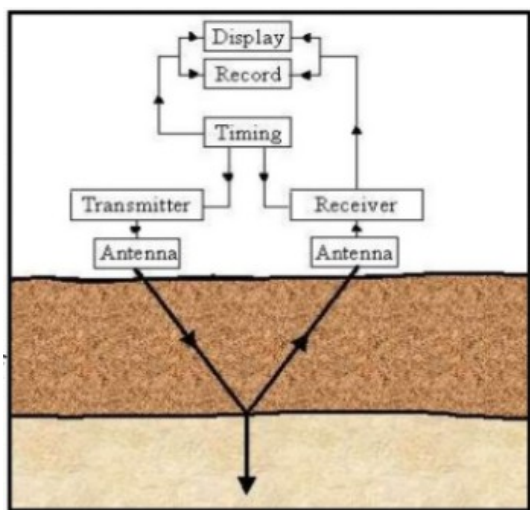


Figure 10: Working principle of GPR [32]



Figure 11: K10 “Black” CRUX GPR [33]

GPR systems are available commercially from various manufacturers such as Geophysical Survey Systems Inc. (GSSI) and GeoSearches Inc., among others. Some standard software prevalent in use with the GPR system is RADAN, GPRmax, GPR-SLICE, etc. The relative simplicity of the GPR system allows for easy installation on a robot system [35, 33]. For instance, CRUX-GPR was developed by the NASA JPL for the “Construction and resource utilization explorer” (CRUX) project. Further, this CRUX-GPR was also mounted under the chassis on the K10 “Black” robot system, as depicted above for underground mapping illustrated in figure 11 [33]. A control unit is needed for the operation of subordinate components and signal processing as well a display unit to generate a cross-sectional profile for the scanned area. Lastly, to maneuver the rover system mounted with GPR inside the deposition tunnel, a continuous power supply is required [34].



GPR technology could be an attractive option for C/S activities at an underground repository since it provides a continuous real-time cross-sectional profile without drilling or digging the surface. Also, it can detect unspecified underground voids and trenches in the repository. Therefore, apart from surveillance activities, it will also be useful for verifying design information. It comes with a considerable range of frequency (1MHz-5GHz) to choose from depending on the requirements of resolution and depth of penetration.

Potential challenges associated with operating GPR in an underground repository may include power system requirements and maneuverability. Also, the selection of low or high frequency will require the depth of penetration and sub- surface image resolution trade-off. Ultimately, the method still needs validation under realistic conditions before GPR can be realized for monitoring purposes.

#### 4.1.5 Ultrasonic Evaluation

Like the unique RFID tag of the waste canister, friction stir welding (FSW) creates a unique signature between the lid and the tube of canister related to the variation of the internal gap. Specifically, the waste canister made of copper consists of a bottom plate, a tube, and a lid. After the fuel assembly is encapsulated inside the copper canister, it will be sealed using the friction stir welding process. However, this process of joining copper surfaces leaves an internal air gap between the surfaces. The internal gap magnified image is shown in figure 12.

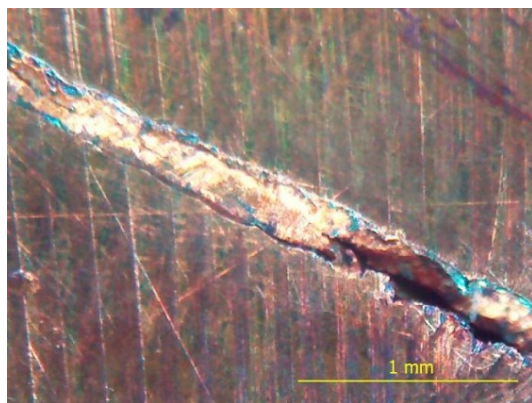


Figure 12: Internal gap after FSW(zoomed image) [28]

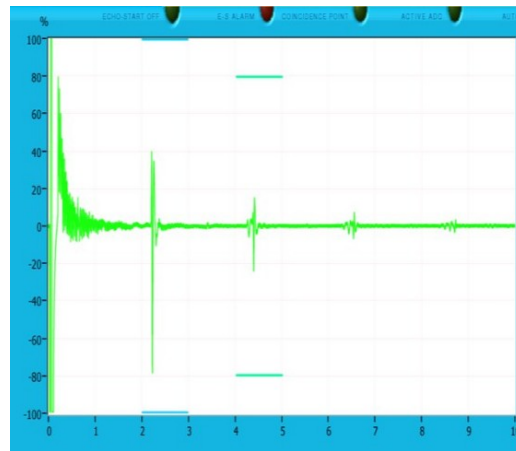


Figure 13: Visualization of ultrasonic amplitude response due to internal gap [28]

This internal gap represents a discontinuity pattern related to the change in the gap height that is unique to the canister. Therefore, the investigation of the welding area between the lid and canister tube could establish the integrity and authenticity of the copper canister. This specific discontinuity pattern can be successfully detected by an ultrasonic transducer [28]. Ultrasonic transducer at 10 MHz of frequency acquires ultrasonic amplitude response, which could be used as a unique signature for each canister [36]. A capture of the ultrasonic amplitude response is depicted in figure 13.

This inspection technique has been researched in detail by the SKB for KBS-3 repository model [37]. Therefore, this technique is very useful for verification upon the receipt of the copper canister at the repository before emplacement. Furthermore, the ultrasonic transducer/probe is amenable to be installed on a robot system [38].

Therefore, this method, when used in conjunction with other C/S measures could be useful to establish integrity and

aid in detecting tampering or diversion attempts in pre-backfill repository environments. One of the possible advantages of this inspection technique is that it could offer unique identification tagging for the waste canister. This intrinsic fingerprint of the internal gaps could be used to establish the integrity of the waste canister until backfill. However, one of the possible challenges of this inspection method is its limited validation for an underground repository situation, and the lack of regular access to the weld on the canister.

#### 4.1.6 Measurement and Detection of Radioactivity

IAEA safeguards measurements are performed at gross, partial, and bias defect verification levels. Gross defect verification can be used to ensure that the waste canister is not replaced with dummy material. Partial defect verification ensures that no significant bulk material is removed, and bias defect verification ensures that no small quantities of bulk material are removed. Independent verification of spent nuclear fuel defect levels will require the use of nondestructive assay (NDA) methods. The waste canister could be checked for isotopic composition, burnup, and cooling time data just before emplacement with the help of NDA methods. Subsequently, after a waste canister is emplaced, C/S measures could be used to maintain the CoK of nuclear waste material. Also, a procedure to predict the radiation signatures for buried waste canister will be discussed in the paper, which can be used as a possible gross defect verification measure if the radiation signature is significant with respect to the background.

Since the encapsulated nuclear waste is ready to be deposited inside the underground repository, passive NDA measurement methods are expected to be preferred from a safety perspective. Because the radiation emitted by nuclear waste will be attenuated by both the copper and cast-iron canister, passive NDA methods will likely be limited to the measurement of gamma-ray and neutron fields.

Passive NDA technologies for gamma-ray and neutron measurement are widely available from many commercial vendors. Examples include probes such as the in-situ object counting system (ISOCS), the safeguards mixed oxide python detector (SMOPY) and the fork detector [40, 39]. Fork detector measurements of gamma and neutron intensity, supported by calculations from isotopic transmutation and depletion software such as ORIGEN [41], are used to verify operator declared data [42] both in spent fuel cooling ponds and before transfer to dry storage casks. A typical fork detector design consists of an ion chamber (gamma detection) and fission chamber (neutron detection) combined with pre-amplifiers and modular signal processors. Fork detectors are commercially manufactured by ANTECH Inc., and specifically B2102 series are suitable for IAEA requirements. A fork detector is shown in figure 14.

While an off-the-shelf fork detector is unsuitable for direct use in the autonomous inspection of nuclear repositories, data gathered from its use in spent fuel pools and during transfer to dry storage could serve as a comparison for radiation field measurements taken after emplacement by an autonomous vehicle.



Figure 14: Fork Detector [42]

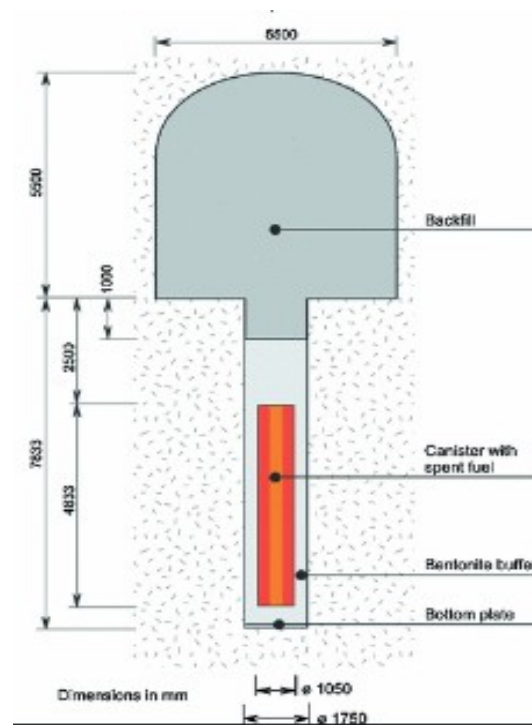


Figure 15: Copper canister covered with bentonite clay buffer [43]

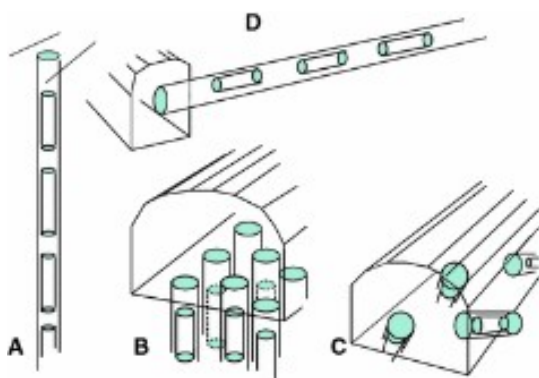


Figure 16: Copper canister deposition scheme inside deposition tunnel [43]



Figure 17: UAV mounted with thermographic camera [49]

Recently, a radiation detecting robot system mounted with a Geiger counter, a camera, an LCD screen, and Xbee modems controlled by an Arduino microcontroller was used to travel through and characterize highly radiated areas [44]. It may be feasible to adapt a similar system to an autonomous robot.

The nuclear material characteristics of spent fuel such as decay power, isotopic inventory, and radiation source terms can be numerically predicted as a function of time post waste canister emplacement using the ORIGEN module of the SCALE [45] code system. The predicted values can be directly compared with the measurements obtained from passive NDA methods for gross defect verification. Computational models based on modern radiation transport codes such as MCNP [46] can be used to assess the impact of the attenuation of the encapsulation on the radiation signature of nuclear waste. In the KBS-3 repository design, for example, the canister, after being placed inside the deposition hole of the deposition tunnel, is surrounded by a bentonite clay buffer. A typical cross-section example [43] of copper canister buried inside a deposition hole is depicted in figure 15. Assuming 662 keV gamma rays and a polyvinyl polymer-coated bentonite clay [47] with a density of 2.8 g/cc, 70 cm of the buffer will cause the gamma-ray signal to be attenuated by at least a factor of  $10^8$ .

A passive NDA method could be used post emplacement and before the backfill process is initiated *only* if the radiation signature is distinguishable with respect to the background. One of the most important advantages of this method is that it is the most direct method to establish the veracity and integrity of the presence of nuclear waste material inside a waste canister. However, the disadvantage is that the post emplacement radiation signature of nuclear waste might be reduced to very low levels, and as the operation time of the repository is increased, the radiation signature will further decrease due to the decay of radioactive material. Potential gamma detection techniques include gross counting using a Geiger counter or spectroscopy using a low-resolution sodium iodide (NaI) detector or a medium-resolution cadmium zinc telluride (CZT) detector. It is unlikely that a high-resolution detector such as high purity germanium (HPGe) would be viable for use on an autonomous robot. Similarly, a small neutron detector could be deployed. Example detectors could include He-3, BF<sub>3</sub>, or Li-6 and ZnS(Ag). One benefit of neutron detectors is that they would differentiate special nuclear material from other benign or nuisance sources. A gamma system with the same capability would require some level of spectroscopy. A drawback of most NDA systems is the need for additional electronics and analysis/processing software. There are some commercial self-contained systems such as those used by first-responders which may provide a viable alternative, may even be able to combine gamma and neutron signals, and could meet requirements to be mountable to a rover system.

#### 4.1.7 Temperature Profile Measurement

Like the characteristic radiation signature, the decay power (heat) of a fuel assembly depends on its burn-up, age, and mass of radioactive material. Decay heat can also be estimated using SCALE/ORIGEN or other similar software packages. With knowledge of the decay heat source term, the temperature in the buffer region of the repository can be estimated using modeling and simulation software such as ANSYS [48]. Some representative copper canister deposition schemes are shown in figure 16. The computed temperature at the buffer's surface can be compared with the actual temperature measured as a qualitative material accountancy technique.

Surface temperature measurements can be performed using an infrared thermographic camera. A thermographic camera works on the principle of detection of infrared radiation (wavelengths as long as 14,000 nm [50]) emitted by an object. A thermographic camera is also amenable to robot system installation [49]. A robot system mounted with a thermographic camera is shown in figure 17. Infrared thermography can be performed from the air through a UAV to generate a thermographic mosaic [49]. One of the possible advantages of this method is that it can be used to establish the qualitative verification of nuclear waste material. However, the thermal power of the waste canister decreases with the operation time of the repository, which makes it less likely that a distinguishable thermal signature will be associated with the waste canister. Infrared thermography is only practical before the backfill is initiated.

## 4.2 Levels of Automation

A robotic rover can augment direct IAEA inspections of the geological waste repositories by providing the inspectors with an extension of sensing capabilities. Beyond the validation technologies which characterize the robotic rover's sensing capabilities, a large consideration must be made to the automation capabilities. Specifically, the method by which the robot rover maneuvers around the environment requires additional research and adaption to different repositories to take full advantage of robotic automation benefits. This section describes three different methods of operation, each with their own advantages and disadvantages. Each method may be the proper solution for IAEA inspection depending on many external factors such as timeline, repository environment, budget, and technological availability. Further research into each method is encouraged to fully evaluate feasibility of each method.

### 4.2.1 Full Autonomy

Fully autonomous solutions encapsulate the common perception of robotics where a robot can self-manuever and accomplish tasks with minimal to no human intervention. In practice, this requires a large amount of research and development to implement a truly hands-off system. A fully autonomous system can allow an IAEA inspector to deploy several robot systems at once to complete the inspection without each system overloading the attention capabilities of the inspector. In the case of remote inspection implementation, multiple systems can be deployed at once with the operator simply monitoring for status of each robotic system. This can provide strong efficiency gains from current inspection techniques.

Autonomous robotics is currently a research topic which is drawing a lot of attention. The field of study delves into various aspects of autonomy such as unknown environment navigation, task allocation and scheduling, robotic localization, path planning, and multi-robot coordination.

Some examples where these fully autonomous aspects may be applied to IAEA inspection methods to underground waste repositories are given, but further detailed research is recommended for each specific nuclear repository. Exploration of unknown environments require algorithmic challenges that processes the perception information (e.g., LiDAR scans, camera images) and returns a direction of desired travel. Even with the given ground truth information of repository design layouts, different deviations and potentially undocumented drifts may be present which require these approaches. A popular method, frontier-based exploration algorithms, has proven successful and has been commonly applied in the robotics community [51, 52, 53, 54]. In another example, task allocation and scheduling can be applied to organize sub-objectives alongside the main objective of nuclear



inspection. The deployed system would be capable of navigation along the environment, but may encounter a variety of sub-tasks such as plug inspection scheduling or additional deposition hole verification [55]. The algorithm would have to balance parameters such as remaining mission duration time and power supply with the benefits of maximizing plug inspection versus deposition hole verification. These kinds of desired mission outcomes can be programmed beforehand by the operators. Finally, the last example considers the case where multiple robots may be deployed at once into the underground repository. This can enhance the efficiency of the inspection trip by increasing the amount of ground covered. When these robots are deployed, they would require scheduling and coordination amongst each other to maximize parameters like ground covered with most amount of inspection goals accomplished [56, 57]. Furthermore, this kind of multi-robot coordination would need to consider the potential drop in communication between each robot and plan accordingly in a decentralized manner [58, 59].

#### 4.2.2 Shared Autonomy

A shared autonomous solution can incorporate desirable elements from fully autonomous or manual approaches at a more reasonable complexity. Shared autonomy involves a mixture of fully autonomous routines with human interaction and control. This approach can be flexible and adapt to certain situations at the cost of certain capability trade-offs. Furthermore, a shared autonomous solution can be implemented as a stopgap between the manual and fully autonomous approach, with incremental features developed and implemented at separate times. An example of a shared autonomous solution can involve waypoints and certain task commands issued by the inspector. The robot may then begin to execute on these commands in an autonomous fashion, reverting to manual operation for more complex, sensitive, or difficult tasks. Additionally, autonomous sub-routines may be installed for the robot to take over if communication with the operator is lost. These routines may simply involve recovery behaviors like backtracking to the last known position within communication range.

Shared autonomy solutions can vary in the degree of human collaboration that is required [60]. Implementations can evolve with advances in technology and algorithms, with the possibility that early implementations of shared autonomy require more operator involvement. Later iterations of the implementations can incorporate more autonomous features, reducing the operating load on the inspectors. Ultimately, continuous improvements on the shared autonomy system can lead to a near or fully autonomous solution.

The shared autonomy solution can incorporate different levels of autonomy mentioned in the fully autonomous section. In addition to the fully autonomous robotics research, the shared autonomy robotics research includes fields like human-robotic collaboration and hybrid control schemes. In the case of nuclear repository inspection, an example of human-robot collaboration would be graphical user interface (GUI) designs which helps maximize the productivity of the IAEA inspector without inspection result information overload. The verification technologies return information in different forms, such as radiation measurement graphs or deposition tunnel backfill quality. The display of these different information to operators can be studied and modified to desired traits like maximizing the operator's interaction with the rovers [61, 60].

Understanding of human-robotic collaboration can also include the creation of an input control system (e.g., joystick, controller, keyboard) which can be easily operated or send information back to the robots. Depending on the complexity of the automation, a more complex input control system with more total inputs available may be required. An example of hybrid control schemes would facilitate interactions with the human during navigation and rover motion. Specifically, if the IAEA inspector observes an area of interest, the operator can designate the task for the robot to execute the inspector's order. Upon closer inspection of the area interest, the inspector may desire manual control in order to have a more detailed search. This alternation between autonomous self-guidance and manually controlled can require a flexible control scheme which is capable of both types of operation [10]. Next, if the shared autonomy system favors manual operation, there can be autonomous sub-routines built in. These autonomous sub-routines can be executed in the event of loss of communication. If the operator no longer has control and communication with the robot, the robot can execute the autonomous algorithm which enables it to return to a last known position of communication range. Another example with communication loss can occur

during inspections of undeclared tunnels or sections. Autonomous inspection routines can be built to be executed if the area of interest is outside of communication range and then return into communication range.

### 4.2.3 Manual Teleoperation

Lastly, robotic teleoperation is a fully viable solution which has been used in a variety of applications [62]. In this operation mode, the operator has full and direct control of the robot's motions and planning capabilities. An example of manual operation would involve the operator sending motion commands to the robot from the base station based on visual feedback obtained by the rover using onboard sensors. This base station can be on-site at the geologic repository or remote in another location, provided constant communication is maintained.

The teleoperation option is the easiest to implement based on the pedigree of the technology. However, the performance of the system is highly susceptible to communication quality between the operator and the rover. Furthermore, it also requires substantially more operator training. Practical implementation of this technology would require a permanent communication network to be setup along the main and deposition tunnels in the underground facilities, which would expand alongside construction. Another implementation could be a temporary communication network set up by the robot, which drops retrievable communication nodes along the way [63, 64]. While the technology is easy to implement, it has the downsides of requiring the full attention of the operator. This limits the ability to deploy multiple robots, thereby likely reducing efficiency gains that would be had with more autonomous solutions.

## 5 Technology Implementation

The safeguard requirements, robot sensing modalities, and the robot operation methodology sections provided research on and components of an operational and complete system capable of augmenting the IAEA underground nuclear repository inspection task. This section addresses how different robot sensing modalities in Section 4.1 may be combined with the operation methodology in Section 4.2, in order to fulfill the safeguard requirements outlined in Section 2 with the highest confidence. First, an example of a robot system implementation is provided. The second section describes various IAEA inspection scenarios capable of being conducted by the example robot system. Lastly, a high-level financial estimation of implementing a capable system is provided based on similar projects.

### 5.1 Robot Inspection System Example

This section provides an example of a robot system capable of augmenting the IAEA inspection process of the requirements outlined in Section 2. The example robot system will be kept at a high level with varying degrees of specificity, due to the variable environment and generalized inspection problem. Worldwide, nuclear geological repositories are in different stages of operation, many still under construction, with various design plans in progress. In general, an underground environment similar to a mine was assumed to be the ideal environment and problem domain in relating to underground nuclear repository inspection.

Also, it is assumed that a custom robot will be designed and developed for the IAEA inspection process. The customization will allow flexibility in dealing with the various challenges presented by the underground repositories. Additionally, the variability from one repository to another may require different design implementations or sensing modalities. Commercial robots do not seem to be readily available for mine-like underground environments likely due to the many challenges such an environment presents. In order to address these challenges, a robot would require above average resistance to elements such as water and dust, be required to traverse potentially rugged terrain filled with small to medium sized rocks, and possibly communicate in a bandwidth restricting environment. These challenges are best addressed with a custom robot which would not be constrained by the manufacturer's design.

Finally, a custom robot allows for extendability to future sensors or other components that may be of use and can be easily added.

The following robot inspection system example is derived from similar robots in similar environments [65, 66, 67], thereby supporting the selected specifications. The focus is on the hardware specification here for a few reasons. The first is that a lot of the development time will involve the software. Creating full or shared autonomy software is still a large research and development field that requires an extensive amount of testing alongside the initial development. Furthermore, it is likely that the software will be highly customized due to the novel robotics application. However, it is unlikely the entire software stack needs to be written from scratch as there are a lot of packaged algorithms out there, but software development will be needed.

### 5.1.1 Baseline Hardware

This section covers some hardware examples and components which are not explicitly applicable to nuclear repository inspection but is mandatory in any robot system. First, in order to move the robot chassis and the payload, motor controllers and actuators are utilized. The motors will likely be connected to rugged wheels for locomotion. Alternative propulsion methods can be explored, such as continuous tracks, treads, or Mecanum wheels based on system and product requirements. However, these alternative methods can be more complex, despite providing additional features (e.g., Mecanum wheels allow omni-directional movement), and may encounter maintenance difficulties with the terrain of the repository and get jammed up more frequently. In addition to locomotion, a high-level control system comprising of a CPU and GPU(s) are necessary for major system operations. These operations include processing the sensor data, communicating with the base station, and controlling the lower level motor controllers for motion. As the number of on-board sensors increase, the computational demands by the sensors increase and thus increasing power draw. This is an important consideration in the build out of the custom robot system in order to maintain a balance between inspection capability and robot operational power capacity.

Thirdly, these hardware components require power, and this usually comes in the form of a battery system. Combustion engines have been used in mine environments [10], however this is largely driven by power requirements of the robot's locomotion system and payload. Additionally, combustion engines produce fumes and pollution which can contaminate the environmental readings of nuclear inspection sensors. Deep-cycle batteries have been used on autonomous robots in the DARPA Subterranean challenge, providing a few hours of operational time [65] with similar sensor payloads of around 50kg [66]. In addition to sensor power draw, robot system weight and the desired area of coverage will determine battery specifications. Operational tests will be the best indicator of system battery performance.



### 5.1.1 Inspection Hardware

The following hardware could be utilized in the inspection process and part of the robot payload. A variety of optical sensors (LiDAR, RGB and Thermal Cameras) are suggested due to their low weight and power draw of only around 10% with respect to the overall power distribution of the robot's other components [67]. The blind spots of the optical system are generally covered during movement of the robot, but testing is recommended for the optimal number of sensors.

1. LiDAR Sensor (x2): The LiDAR sensor is capable of full 360 degrees planar scanning in the horizontal with the limitation being the vertical FOV around 30 degrees. Wide coverage can be accomplished with two LiDAR sensors. One mounted, scanning parallel to the ground for horizontal mapping ( $\pm 15^\circ$  from  $0^\circ$ ) and another scanning perpendicular to the ground for high vertical mapping capability ( $\pm 15^\circ$  from  $90^\circ$ ).
2. RGB Cameras (x3 - 5): A large number of cameras would provide full visibility and reduce the number of blind spots, with higher amounts capable of eliminating any blind spot. For example, five cameras would cover the full 360 degrees if each camera had a field of view (FOV) of 72 degrees. More cameras can be added if the upward view is requested or convenient for inspection operators.
3. Thermal Cameras (x1): The single camera can be targeted towards specific regions of interest with more added if additional thermal field-of-view information is desired. The power draw is expected to be similar to RGB cameras. The camera can also be mounted on a small actuation device to provide directional capabilities during shared autonomy routines.
4. LED Lights: Illuminates the environment and provides consistent lighting for optical cameras. Testing will be required for optimal number and luminosity strength of LED lights. This is also largely dependent on the lighting conditions in these underground repositories, which can be expected to be equivalent to underground mines.
5. Ground Penetrating Radar (x1): Portable and effective ground penetrating radar sensors [68] can provide depth sensing up to 5m with resolution around 15cm or sensing depth up to 50m [33]. GPR is an uncommon technology used in mobile robotics which requires additional testing and research on power draw, however, the initial testing by NASA indicates this is a viable technology for robotic use.
6. Handheld Magnetic Wave Tag Reader (x2): Magnetic wave tags, alternatives to RFID and/or bar codes have been tested on DOE certified waste drums and have been observed to function properly at ranges up to 4.61 feet [27]. These tags can store and transmit data on temperature, humidity and pressure and can be read using a mobile handheld featuring a secure, two-way IEEE 1902.1 wireless data link ruggedized to meet MIL-STD-810G.
7. Radiation Sensors (x1): Radiation will be detected with small, low-power gamma and neutron counters. Post emplacement and backfill, signals substantially above background will be indicative of off-normal conditions in the repository. Gamma detection options could include plastic scintillators, proportional counters, or if spectroscopy is desired, room-temperature CZT crystals. Neutron counting technologies include  $\text{BF}_3$  or  $^3\text{He}$  gas proportional counters and fission chambers.

### 5.1.2 Communication Hardware

In these cases of remote robot operation, an underground nuclear repository presents an environment which restricts communication between the base station, where the IAEA inspector is situated, and the robot system. This restricted environment is due to not only the distance between the robot and the base station but the amount of geological and man-made material between the underground repository and above ground facilities. In the case the underground repository is equipped with a wireless communication system, such as Wi-Fi, robot communication hardware may not be necessary. The robot can simply communicate with the existing system in the underground repository. However, the creation

of additional drifts for emplacement and subsequent backfill may mean this is not possible or there will be areas without readily available communication systems. In this case or when pre-existing communication networks are not present, the robot can create a portable communication network as it traverses the repository [69, 70]. There have been practical applications of robot systems dropping nodes along the mission to continually establish communication with the base station while exploring unknown environments [65]. With regards to underground repositories, these nodes would need to be dropped in locations which are unobtrusive to normal repository operations and retrievable by the robot system at the end of the inspection mission.

### 5.1.3 Size and Footprint Considerations

The size and footprint of the custom robot system must be considered when discussing the feasibility of robotic augmentation of IAEA inspection processes. A large robot the size of an automobile would likely not be feasible in the constrained environment of underground repositories. Furthermore, transportation to and from the facilities would be more difficult as the size of the system increases. Lastly, a larger chassis would lead to heavier weight, thus increasing the power demand of the system. However, a larger system would be able to accommodate more inspection hardware mentioned in Section 5.1.2. A comprehensive evaluation would be recommended to find the optimal number of inspection sensors and type while meeting inspection capability requirements.

Optical sensors like LiDAR, RGB, and thermal cameras are relatively lightweight and have small dimensions, allowing multiple sensors to be coupled together in a smaller system. Some examples of these systems can be found in the robots competing in the DARPA Subterranean competition [65, 66]. These robot systems have much smaller footprints which are comparable to half the size of a bobsled. A smaller system footprint is necessary for robots to be maneuverable throughout the environment and inconspicuous to the facility workers in the repository. Furthermore, the width of the emplacement tunnels are reported to be around 4.2m with a similar dimension for height [71], which provides a reference constraint for design of the robot system dimensions. Additional inspection sensing modalities like GPR and radiation sensors would require testing and development in order to identify the space requirements.

## 5.2 Safeguard Inspection Implementation Scenarios

According to the IAEA, the main safeguard requirement for the underground section of nuclear storage repositories will be satisfied through Design Information Verification (DIV) [6, 72]. The IAEA intends to verify the facility design through physical inspection and various containment & surveillance (C/S) methods. This section shows how a robotic system can be capable of autonomously or shared autonomously traversing the repository and providing surveillance methods which can be used as part of the DIV process. This section provides inspection scenario examples of a robotic system configuration generated from Section 4.1 on robot sensing modalities and from Section 4.2 on robot operation modes. The robot system described in this section can be the main surveillance mechanism by which most of these assurances are satisfied during each IAEA inspection.

In addition to augmenting safeguard approaches and IAEA inspection, the robot system is also capable of auxiliary requirements by the IAEA in satisfying the Integrated Safeguard Verification System (ISVS) for a nuclear repository [4]. The ISVS holistic system covers the repository and contains elements of C/S, monitoring and non-destructive assay (NDA), as well as DIV, geophysical, environmental and radiological systems, as applicable. In addition to the safeguard approaches, the ISVS should have high system reliability and capability to detect component failures, as well as remotely notifying the IAEA of any failures. The reliability of a robot system requires extensive testing but is

similar to any other technology adoption process. Lastly, the integration of an onboard computer allows the robot to constantly log information and maintain health status updates to the IAEA.

Regarding the selection of the robot operation mode, the efficacy of the robot operation mode for each technology or task ultimately resides in the execution of the implementation. These operation modes (full autonomy, shared autonomy, and manual teleoperation) are selected based on examination of the current state of the art with respect to the task or application, as well as the time and cost of implementation. The time and cost of implementation are driven by the difficulty and novelty of the algorithms expected in the methods of operation. For example, in DIV mapping via full autonomy, algorithms like SLAM are well studied and there are plenty of libraries/packages available. Additionally, there are many applications being researched and developed for autonomous mapping. However, defect detection for plug surfaces is a more novel application. The likely approach would involve deep learning, as tools like convolutional neural networks (CNNs) have provided the best results in object detection and feature recognition. Since no direct applications of deep learning currently involve defect recognition for deposition tunnel plugs, the networks need to be trained in order to have practical confidence. Finally, nuclear specific applications involving sensor fusion of different sensing modalities (temperature, radiation, etc.) likely require more research, training, or software development to implement in an autonomous fashion.

This would require a cross-disciplinary effort involving nuclear domain knowledge. As such, now, these methods are likely best left for shared autonomy applications by a trained IAEA inspector.

### 5.2.1 DIV Technology Implementation Scenarios

DIV is a process that heavily relies on individual inspector knowledge and experience. The novel, restrictive, and expansive environment of the underground repositories will present significant challenges to traditional DIV approaches. Any DIV process shortcomings will be even more apparent when applied to underground nuclear repositories. For example, inspectors heavily rely on 3DLRs (3- Dimensional Laser Rangefinders) to draw attention to areas of interest. These 3DLRs are heavy and can be clumsy to carry and would be a burden to the inspector trying to cover the large underground repository grounds. Robotics has already been considered for augmenting DIV approaches [73] since they can access areas that are unsafe and inaccessible to safeguard inspectors. These robotic systems can be the main method by which the inspectors obtain DIV information, through remote operation (either on site or farther away).

During the pre-operation phase of the repository, an initial formal DIV can be conducted with the same robotic system intended for regular inspection, as well as more capable but less portable systems like 3DLR technology. The IAEA currently conducts DIV at various surface facilities using 3DLR technology due to the high resolution and comparison capability [73]. However, training and operational difficulty of the technology decreases the feasibility of 3DLR application to underground repository inspection. Regular DIV inspections during the operational phase can rely on several of the listed technology combinations in order to provide repository DIV assurances. These technologies can address DIV assurances outlined in Section 2.0.1, as well as ensuring that design changes are verified through comparison to baseline information.

1. **LiDAR + Full Autonomy, assurance (1, 3, 4, 5):** Large scale mapping is critical to satisfying DIV requirements and robot systems have been shown to be capable of autonomously accomplishing these kinds of tasks. As mentioned in section 4.1.1, LiDAR technology can be combined with robot odometry to create high fidelity maps suitable for DIV, on the order of +/- 2cm within the actual position [73]. LiDAR has been used in various applications and environments similar to underground nuclear repository inspection [65, 66, 67, 73, 74]. Additionally, this sensing modality has great precedent and synergy with autonomous robot

applications [75, 76]. These maps can be continually gathered during each inspection run and subsequently compared to historical data and reference data.

2. **Optical Imaging + Shared Autonomy, assurance (2, 3, 4, 5, 6):** Repository DIV also mainly involves verification of proper seals and closed off areas, particularly pertaining to side tunnels where the nuclear materials are emplaced. An optical sensor like a camera can provide real-time feedback to an operator, allowing visual detection of voids or aberrations which are not consistent with regulation. Object recognition and flaw detection fall under the machine vision area of research which receives a large amount of attention from academia and industry alike. There have been many autonomous applications of automatic defect (e.g., voids, cracks) identification in other domains [22, 77, 78, 79, 80], however some domain-specific development would be required in order to make this a fully autonomous routine. Specifically, for DIV assurance 2, the imaging might have a difficult time identifying different materials from optical recognition alone. It can find voids and other flaws but identifying softer or different materials might require tactile tests if there are no visual distinction from baseline materials. Furthermore, the inspection area might be larger than a single field of view (FOV), requiring multiple viewing angles and robot maneuvering. Initial system implementation can involve the operator taking over for the dexterous robot movement. Later system implementations can transition to a fully automated routine based on information maximization using active perception [81, 82]. Finally, a tactile sensor can be utilized in cases where visual inspection is not enough to differentiate material composition to validate proper material characteristics (e.g., hardness).
3. **LiDAR + Optical Imaging + Full Autonomy/Shared Autonomy, assurance (1, 6):** As mentioned in [6, 73], DIV also involves the tracking of declared equipment throughout the facility. In this case, the list of identified equipment can be visually tracked using object detection with the optical imaging and the location of each equipment located onto the constructed map. The dimensions of these equipment can be referenced to the DIV map to ensure that the allotted occupied area falls within guidelines. Fritzell [6] provided examples where undeclared equipment could be used for diversionary activities. Through a combination of object detection and mapping, features like location and dimensions of the identified equipment can be tracked and logged. This can be done autonomously as seen in these similar applications [83, 84] with control reverting back to operators if objects or areas of interest are discovered. There would be a need to train the network on the declared facility equipment that is desired to be tracked. An example of object detection is shown in Figure 18.

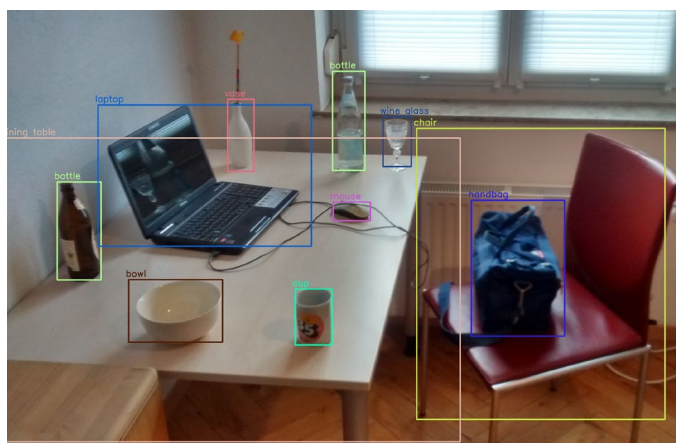


Figure 18: Object detection using the YOLO algorithm [85]

### 5.2.2 Portable C/S Technology Implementation Scenarios

In order to accomplish design information verification of a nuclear repository, sensing modalities must be used by the inspector or robot. In the case of human inspectors, they use their visual, tactile, auditory, and perhaps even their olfactory senses augmented with portable and semi-portable technologies. With

robotic systems, different modules of sensors may be used to increase the capabilities of the robots and provide a mobile capability to the surveillance component of containment and surveillance (C/S) approach. These portable C/S systems can be used in conjunction with the robotic DIV methodologies in order to further satisfy safeguard requirements that are not possible with traditional C/S approaches. The traditional C/S approaches are static methods aimed at monitoring egress points and material flow locations but are incapable of maintaining continuity of knowledge in areas beyond the method's fixed location.

This section explores other sensing modality implementations which directly tie to containment and surveillance methods. Additionally, each implementation is related to one or more C/S requirements stated in Section 2.0.2. Some of these suggested methods are focused on dynamic and variable components of the underground repository such as thermal properties of emplaced canisters and environmental readings of contamination. This data can be stored and compared during each inspection to historical data to make sure it is within acceptable values and not highly deviated from the norm.

The portable C/S technologies are not able to consistently satisfy requirement 1 from Section 2.0.2 due to the cyclical nature of the inspections. To ensure continuity of knowledge from above ground activities, traditional C/S measures must be utilized. All subsequent suggested C/S implementation scenarios are capable of being tamper resistant and have low false alarm frequencies but require additional development. Regarding requirements 6 and 7 of the C/S system requirements, tamper protecting of the device could involve physical seals and locks around the robot system and sensor. Furthermore, testing and development of authentication methods of the sensor data would be necessary in order to ensure the authenticity of the data stream and captured information.

1. **Ground Penetrating Radar + Shared Autonomy, requirements (2, 3, 5):** Autonomous inspection with GPR has been accomplished by NASA using their portable CRUX GPR technology [33]. The technology was capable of depths up to 5m and resolutions within 15cm [68] but was targeted towards lunar environments. NASA has also developed a GPR for use with the martian environment which was capable of depths up to 50m [33]. These portable technologies can be used by the inspection robot system in conjunction with thermal sensors in order to verify location and presences of emplaced canisters for a dual C/S system.
2. **Thermal Imaging + Full Autonomy, requirements (2, 3, 4, 5):** A thermal camera mounted on a mobile robot is able to capture thermal information as the robot traverses the facility and is able to map out areas inaccessible by the static C/S surveillance approaches [49]. Heat maps of the facility can be matched against historical data with thresholds pre-determined to calculate potential diversionary activities. This passive sensing technique can be fully autonomous through continuous thermal data collection during the inspection operation or set to a determined frequency in order to reduce power draw.
3. **Thermal Imaging + Shared Autonomy, requirements (2, 3, 5):** In addition to the fully autonomous thermal sensing, the thermal camera can also be used at the inspector's discretion to examine areas of interest. Specifically, the thermal camera potentially can be used to match thermal profiles of emplaced canisters underneath the Bentonite clay cap at the end of the emplacement tunnel. The operator could take control to inspect these emplaced canisters before the backfill process to additionally verify the presence of the canister, thereby maintaining CoK. This verification process would require extensive modelling and testing in order to approve of this technique as a sound inspection method. In the future, fully autonomous inspection routines can be conducted in a similar vein to the second suggestion in the DIV implementation scenarios, optical imaging using shared autonomy. An example of thermal imaging used in the nuclear domain is shown in Figure 19.



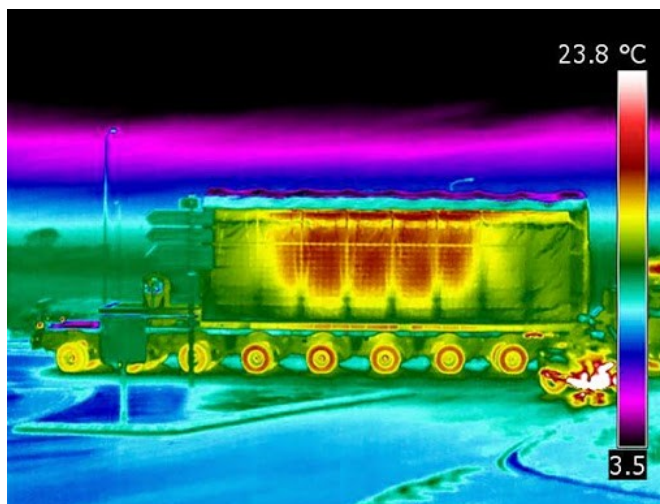


Figure 19: Thermal image of railcar CASTOR system [86]

4. **Environmental Sampling + Full Autonomy, requirements (2, 4, 5):** A portable alpha-beta particulate monitor can be mounted to the robot and set to collect data in a pre-determined frequency during the fully autonomous mapping routine. The data can be overlaid over the generated map to produce a “heat” map of the level of contamination throughout the facility. During each inspection run, this data can be continuously collected and compared against historical data for significant deviations. Additionally, other environmental sampling methods can be used, targeting specific elements that relate to a specific nuclear signature” [87]. There is already a significant amount of research and testing on the proper nuclear signatures for IAEA safeguarding [88, 89, 90, 91]. However, most of these nuclear signatures requires the use of mass spectrometry which is accomplished by a bulky and non-portable mass spectrometer. Swipe sampling can be utilized for offline measurements of the samples. In this case, there can be predetermined locations and areas for sample collection or shared autonomy can be used and control transferred back to the operator. Afterwards, the operator can determine the specific locations for sample collection [91, 88]. The measurements can be conducted offline and the locations of the samples mapped to the DIV map generated during the inspection routine.
5. **Radiation Monitoring + Full Autonomy, requirements (2, 3, 4, 5):** Since its inception, the fork detector has gained utility because of its portability. Furthermore, the fork detector is amenable to be mounted on a robot system due to this ability. EURATOM and IAEA have proposed to use this technology for safeguards verification before emplacement inside an underground repository [42]. Post emplacement, small low-power gamma and neutron counters can be used to detect off-normal repository conditions, given that the background levels of radiation will be very low due to the presence of the buffer material. Comparing the expected signal with the measured signal could then be used for real-time safeguards verification.

## 6 Conclusion

Implementing robotics for underground nuclear repository inspection will be a novel venture for the IAEA. Many different factors must be considered in order to fully justify initial research and development, much less full on adoption, of the technology recommendations. This paper presents a variety of robotic technology recommendations that can augment IAEA inspection of underground nuclear waste repositories during the operation phase. The sensing technologies section outlined hardware which can maintain continuity of knowledge of the nuclear waste, adhering to the IAEA safeguards. The

levels of automation section highlights three different modes of robot software implementation and operation by which the robot(s) can execute the inspection objective. The long-term purview of these nuclear repositories allows significant flexibility in the design and implementation of robotic inspection technologies. Technology recommendations that are infeasible now can mature by the time these geological repositories are fully functional.

## 6.1 Future Work

The technology recommendations and implementation scenarios of robotic inspection of underground nuclear repositories in this paper provides multiple avenues of follow-on work. There are still many questions to be answered and testing to be conducted. In order to begin, Oregon State University's Nuclear Engineering department and Robotics department are planning on working with PNNL to create a technology implementation demonstration using a commercial robot system. One of the technology implementation scenarios from either the DIV or C/S implementation scenarios will be selected for a proof-of-concept demonstration.

Additionally, the sensor information requires capability and specification validation in order to satisfy IAEA inspector's criteria. The stated sensor technical specifications provide a starting point, however, empirical results provide a definitive answer on sensor performance. For example, the DIV map constructed via the LiDAR sensors and full robot autonomy using SLAM can suffer from errors and inaccuracies. This is largely due to odometry deviations caused by encoder slippage or other environmental variables. The extent of the acceptable deviations must be tested in order to receive full confidence as a DIV safeguard approach.

Integrity of the data collected by the robot and the communication between the robot and the base station must be validated and warrants further examination. As briefly mentioned in Section 5.2.2, the robot itself must be tamper resistant and provide indication of tampering. This security requirement extends to the sensor data, information and samples gathered during inspection, and the streaming communication information to and from the base station. Encryption protocols of the data and communication are not extensively considered in this paper and should be explored. Furthermore, research into spoofing of various features that are utilized as inspection criteria and thresholds is necessary. These concerns should be explored early in the robotic system development in order to ensure synergy with system requirements and prevent late-stage changes.

Lastly, additional domain knowledge can be leveraged in order to maximize the potential of on-board sensors. The efficacy of C/S surveillance via thermal profiles of the canisters under the bentonite cap can be explored using modelling software. Also, nuclear radiation signatures in the environment can be catalogued and tested to identify capable environment sampling sensors which can be mounted on the rover. These outstanding questions are not the only ones which warrant exploration and will inevitably lead to other questions. This paper can serve as a starting point to the exploration of robotics for underground nuclear repository inspection.

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