New Developments for Extended Containment and Surveillance of Safeguarded Materials in Geologic Repositories

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ABSTRACT

The U.S. Department of Energy National Nuclear Security Administration's Office of Defense Nuclear Nonproliferation R&D provides funding to early technology readiness level projects to ensure a new generation of technical tools are available to enhance or improve efficiency of safeguard's methods. The focus area presented will be the development of tools that may be used to monitor special nuclear material placed into geologic repositories. Materials under safeguards that are placed into future geologic repositories will require monitoring well into the future. Safeguarding these materials introduces issues regarding limited access, limited or no power, long durations, detection of material and intrusions at long distances, and data security. This presentation will discuss four related efforts aimed at solving existing and emerging problems in containment and surveillance. These efforts involve application of radiation sensors based upon scintillation and laser induced breakdown to detect radiation at a distance while extracting measurements from long optical cables, the detection of disturbance using seismic and electromagnetic (EM) sensors, and the use of quantum encryption for intrusion detection. All efforts ensure that electronics are accessible on the surface while the portion of the system entombed with the safeguarded material is fabricated from long lifetime components that are not intended to require maintenance.

Keywords: Geologic Repositories; Safeguards

INTRODUCTION

The U.S. Department of Energy, National Nuclear Security Administration's Defense Nuclear Nonproliferation R&D (DNN R&D) provides funding to early technology readiness level projects to ensure a new generation of technical tools are available to enhance or improve efficiency of safeguards methods. The focus area presented will be the development of tools that may be used to monitor special nuclear material placed into geologic repositories. To effectively manage high-level radioactive waste (HLW) the initial heat and radioactivity must be allowed to decay to increase safe handling of the waste. Spent nuclear fuel falls into this category of HLW and is typically initially stored in fuel storage pools or in dry casks at reactor sites or in a central handling facility. Publicly acceptable, safe, and environmentally friendly solutions have been researched for the final disposition and management of HLW. The mined deep geological repository and deep boreholes are solutions that have found wide acceptance. [1,2]

Underground geological repositories for storing radiological materials are being constructed or are in use around the world. In the U.S., the Waste Isolation Pilot Plant (WIPP), in Carlsbad, New Mexico, is currently operational and accepting transuranic waste. The deep geological repository closest to being ready for use is the Onkalo facility in Olkiluoto, Finland.[3] The technical aspects of sealing entombed materials and underground repositories to ensure the radiological and nuclear materials remain contained have been deeply studied. [4-7] In addition nuclear semiotics researchers have explored development of enduring methods for communicating messages to warn human populations of the hazards associated with these facilities. [8,9]

Materials under safeguards that are placed into future geologic repositories will require monitoring well into the future. It is important to note that the placement of nuclear material in an underground repository does not constitute the termination of safeguards. IAEA Policy Paper 15 states that spent fuel disposed in geological repositories is subject to safeguards in accordance with the applicable safeguards agreements for as long as the safeguards agreement remains in force. [10] The safeguards approaches employed for this type of long-term monitoring should be credible and maintain the continuity of knowledge of the stored nuclear material.

Safeguarding this nuclear material introduces issues to be solved in terms of limited access, limited or no power, long durations, detection of material and intrusions at long distances, and data security. This presentation will discuss four related efforts aimed at solving existing and emerging problems in containment and surveillance. These efforts involve application of radiation sensors based upon scintillation and laser induced breakdown to detect radiation at a distance while extracting measurements from long optical cables, the detection of disturbance using seismic and EM sensors, and the use of quantum encryption for intrusion detection. All efforts ensure that electronics are accessible on the surface while the portion of the system entombed with the safeguarded material is fabricated from long lifetime components that are not intended to require maintenance. The efforts outlined in this paper seek to meet the long-term storage, safety, and continuity of knowledge requirements of nuclear waste disposal.

Monitoring Special Nuclear Material in a Deep Geological Repository

DNN R&D is investing in the development of technologies to effectively monitor HLW stored in deep geological repositories. The project known as TRIPWIRE is developing and demonstrating a multi-modal sensor system for containment verification of nuclear waste stored in inaccessible radiological and deep underground nuclear waste repositories. The TRIPWIRE system is envisioned to be able to continuously monitor ionizing radiation and electromagnetic fields in the vicinity of nuclear materials buried in a repository. The system will have the capability to report on disturbances with a real- time alarm control station. The main detection system will use long-length scintillating fiber bundles (SFBs) to perform area radiation monitoring. These SFBs will be coupled to km-scale multimodal optical communication fibers that will relay signals to an above ground monitoring unit. Electromagnetic fields, and changes in local dielectric conditions caused by intrusion and soil movement, can be monitored using, ported "leaky" coaxial cables (PCCs). Electromagnetic field monitors and control electronics will also be located above ground. Tamper-indicating self-diagnostic assessments will be done using optical and electronic time domain reflectometry in the SFBs and PCCs, respectively. The result will be a kilometer-scale multi-modal SFB-PCC system which will be tested and evaluated. Simulation and modeling will be used to inform the development and assessment activities. A prototype demonstration of the system's utility at an Idaho National Laboratory (INL) nuclear storage facility is planned.

The principle of operation is to perform simultaneous, real-time monitoring of ionizing radiation and electromagnetic fields next to storage containers in underground geological repositories. This concept of in situ radiation field monitoring of RN waste containers has been previously studied and shown that local real-time monitoring is possible. [11-14] This work seeks to extend the concept to sealed tunnels or boreholes, ensuring long-term stability and maintainability, and will address tamper indication. The monitoring electronic components of this system will be located external to the repository. This configuration will allow detection of undeclared access to a sealed underground repository; detection of non-natural activity in the vicinity of nuclear storage containers and detection of the movement or removal of radioactive and nuclear (RN) materials from the repository. The effort has relevance to nuclear nonproliferation regarding containment verification and is also meant to address the International Atomic Energy Agency (IAEA) Top Priority research and development need (P.5.R2 2018 Research and Development Plan) where preparation of safeguards tools and techniques for safeguarding new types of facilities, including geological repositories is noted.[15]

Enhanced Ionizing Radiation Sensing with Lasers

Lawrence Berkley National Laboratory is investigating a new laser-based method to detect the ambient ionization that would be present following the penetration of sealed nuclear waste containers. This continuous containment verification approach will enable remote detection over hundreds of meters through networks of optical fibers to the underground repositories where the waste containers reside. Each container in the repository will be equipped with one optical-fiber sensor so that any breached container can easily be identified and located. This method does not require underground power or data transfer. The system will be powered above ground and located with the signal analysis station. Through continuous periodic (e.g., hours) monitoring, this method provides continuity of knowledge for a specific container.

The technology under investigation leverages the newly observed phenomenon of monitoring ionizing radiation using electromagnetic radiation [16,17]. The effect of radiation (alpha, beta, and gamma) ionizing neutral air in the vicinity of radioactive material is to elevate the number of free electrons and ions present in the ambient air, reducing the threshold for laser-induced air breakdown seeded by the negatively charged species. This facilitates the initiation of the breakdown when compared to ambient conditions. This phenomenon is the basis for the proposed remote detection of radioactive material through a network of optical fibers that extend into the geological repository.

Many of the currently available monitoring techniques (seismic, satellite, ground penetrating radar) provide no information about the radiation from the stored material. Radiation detection is, however, paramount for the correct understanding of containment verification, whether a storage cask has been penetrated, is leaking, or has had a seal opened. Direct monitoring of either the chemical signatures or the radioactivity from the material in the repository is a more direct approach to detect specifically a containment breach.

There is currently no mature approved safeguards technology to remotely monitor chemical signatures or radioactivity and verify containment deep underground. While there are traditional radiochemical analytical techniques, they will be hard to implement in underground facilities. The direct detection of radionuclides is a more direct and straightforward approach. The use of enhanced ionization radiation sensing with lasers considers a new method for indirect radionuclide detection that enables remote detection. The proposed technology is based on the use of lasers to detect radioactivity levels that would result from a breach and fulfills all the requirements for containment verification in underground repositories.

Briefly, radiation (e.g., alpha, beta, and gamma) propagates and interacts with air molecules in the atmosphere, creating a high concentration of localized but free electrons [16] through primary and secondary ionization. The lifetime of free electrons in air is short, with a lifetime around 10 ns. However, oxygen in air has a high affinity for electrons through a reversible process $O_2 + e^- \leftrightarrows O_2^-$. The forward reaction to form O_2^- is spontaneous but the energy barrier for the reverse reaction is low (0.46 eV). Exciting the O_2^- ion at a photon energy of 0.46 eV or above, equivalent to wavelength of 2.7 μm or below, a free electron will be released from the O_2^- ion. O_2^- ions preserve free electrons in the air by serving as a reservoir. The release of free electrons from this O_2- reservoir can triggered by a laser. The densities of these free electrons and ionized air molecules can be several orders of magnitude (up to 10^6) higher than ambient air in the absence of the radioactive source [16]. This significant difference in the free-electron density is the main scheme for remotely detecting a radioactive plume or cloud. A pulsed laser can be used to amplify these radioactivity-induced electrons and negative ions by laser-induced air breakdown, initiating a dynamic cascade process that leads to the increase of free electrons and ions under the action of a laser pulse. This mechanism is what can improve radioactive source detection.

Measurement of the temporal profiles and strength of the reflected laser pulse are expected to yield signatures that can be measured that indicate elevated levels of radioactivity. The time difference between when the air is excited by the laser and when the laser is reflected will be used to determine the distance of the radioactivity zone from the laser, thereby allowing localized identification of a breached container. Due to the high intensity of the laser pulse the strong reflection signals can be easily detected remotely. Complementary detection methods such as the incorporation of a second laser beam at different wavelengths, and the direct detection of emission of light from the localized air breakdown plasma will also be investigated.

The laser system can be operated above the repository with the laser beam guided through a network of optical fibers. Each optical fiber acts as a sensor and is terminated at a monitoring location as desired inside the underground repository. The optical fiber also serves to transmit the reflected laser beam back to the control tower for measurement. Evaluated radiation due to containment breach will change the temporal profile of the reflected laser beam and thus will provide a timely (near real time) warning signal of breached containment. Preferably, each container inside the repository is equipped with one optical-fiber sensor, which allows easy localization of the breached container. Signals from neighboring fibers can further assist in precisely mapping in 2D the exact breach location, since fibers which are closer to the breached container will be able to pick up lower radioactivity intensity signals to verify the location.

Distributed Multi-modal Fiber Optic Sensing

A Sandia National Laboratories (SNL) and Oak Ridge National Laboratory (ORNL) collaboration is investigation the use of fiber optics as containment verification sensors with two modalities: passive monitoring using strain sensing and as radiation detectors. ORNL is leveraging existing expertise with fiber optics to evaluate how they can be used to show breaches in individual casks using strain measurements. SNL is evaluating how the same fiber optics can be used as radiation sensors by evaluating existing fiber optic radiation detectors. The successful outcome of this research will be a proof-of-concept demonstration that shows how fiber optics can be used to detect the breach of a cask in real time through strain and radiation monitoring. A key component of this project involves research into how fiber optics that detect strain can be modified to detect radiation. Scintillating fibers are a commercialized radiation detection product available from Saint-Gobain, for example, but have not been deployed in the proposed dual-use scenario.

Long-term containment verification with cask-level resolution presents exceptional challenges due to the extreme scale of containers that need to be monitored, the need for real-time breach awareness, and the longevity of the monitoring solution. Telecom-grade fiber optics offers a comprehensive containment and surveillance (C/S) solution for both deep geological repositories and dry cask storage. When a passive fiber network, potentially spanning tens of kilometers, is connected to a distributed acoustic sensing (DAS) instrument, the fiber is effectively repurposed as a sequential array of thousands of back-to-back strain gauges with a spacing of 5 m. The fibers could also be designed to function as a network of radiation detectors that would indicate if radioactive material has leaked due to a breach or has been removed from a cask. This could be accomplished with a scintillator coating on plastic optical fiber, with a wavelength shifting layer added to improve transmission. Considering the flexible form factor of fiber and no known "wear-out" mechanism, individual gauges could be affixed in the proximity of each stored cask and monitoring could persist for decades or longer.

Currently, there are no technologies for active monitoring of waste casks in underground repositories. Security and containment are achieved through physically closing off or backfilling the tunnels where waste casks are placed.

However, fiber optics have been demonstrated for use in structural and thermal monitoring of underground repositories. An experiment in a French underground facility showed that optical fibers are indeed robust and well suited for use in an underground repository environment. [18,19]. These papers describe a successful installation of optical fiber strain sensors in the Andra Underground Research Laboratory in France. Another experiment with fiber optics was conducted in Switzerland, to monitor temperature and strain after closing a spent fuel and high-level waste repository [20]. These examples indicate that optical fiber monitoring is a feasible technology for this environment and can be expected to endure such conditions over an extended period.

Quantum Seal Network

Scientists at Sandia National Laboratories are investigating a next-generation, fiber-optic sensor link that uses quantum key distribution technology for detecting breaches in nuclear waste containers and for transmitting authenticated, spoof-proof sensor data between remotely located repositories and central monitoring stations. This concept addresses the Safeguards mission need for reliable, long-term containment verification of waste materials in casks and drums located in geological repositories. The fiber-based, configurable quantum sensor link will provide ultra-sensitive detection of seal breaches and real-time status checks via ultra-secure delivery of sensor data to inspectors. This type of fiber-optic sensor link could accommodate many potential breach scenarios including those for existing underground geological repositories such as those at WIPP, new repositories under construction as is underway in Finland, and dry cask storage facilities like those in Germany.

The quantum seal network will function as a distributed seal network will consist of at least three parts: 1) the sensor for intrusion detection, 2) the secure channel for delivery of monitoring signals, and 3) the analysis package for signal discrimination and breach identification. The quantum sensor network is volumetric in nature and could be used to create a barrier of storage space and could be emplaced in a vault wall or physical curtain that securely closes and monitors that area.

The main technologies that form the tamper-indicating sensor and the secure fiber transmission channel are elements of quantum key distribution that measure disturbances on the fiber arising from external stimuli and make it physically impossible for the intruder to falsify the transmitted sensor data without tripping the alarms. This latter feature of preventing data-falsification is categorized as "spoof-proof" or "anti-spoofed" within security communities and is unique to quantum-sensor technologies. This advantage and the ultra-sensitive detection are the key quantum capabilities which differentiate this sensor from existing classical ones. The sensor consists of encoded streams of photons that transmit through conventional fiber and probe the container seal along the configurable fiber. This same fiber is linked back to the central monitoring station for shot-noise limited coherent detection of the probe signals. Due to the laws of quantum physics, the optical signals are spoof-proof and provide authentication and channel integrity checks on the sensor network.

The technical basis for the quantum-secure optical fence is the enabling of shot-noise-limited, continuous-variable quantum measurements of ultra-low-light-level signal carriers in the presence of loss and excess noise in the fiber channel. This approach to the quantum seal link will deliver coherent states between the transmitter and receiver and measure the continuous-variable field quadratures associated with encoded photon pulses. The results of the phase-sensitive field-amplitude measurements will be used to verify the quantum correlation between the sent- and received- photon states. If the transmitted and received electric-field amplitudes along a measurement axis show detailed matching up to a threshold level in shot-noise units, then the seal link can be deemed undisturbed. Since the Uncertainty Principle and the No-Cloning Theorem govern randomly modulated coherent states, this correlation directly monitors potential false-data-injection attacks.

The development work for the quantum seal will involve the construction of the transmitter and receiver. These include a narrow-line, tunable, continuous-wave laser, high-speed lithium niobate modulators, and low-noise balanced homodyne detectors for the tasks of generation, control, and detection of coherent states. Calibration of the components will be made to enable on-demand field encoding at the transmitter and high-fidelity decoding at the receiver. Calibration will also take place for the sensor system to establish the baseline loss and noise levels, establishing a threshold for breach detection. The procedures for calibration will make use of the self-referenced continuous-variable measurement protocol developed in earlier work. [21]

If the goals of this new research are met, the quantum seal network design will bring new and secure tamper detection capabilities for containment verification in waste repositories. The seal link will have to capability to tie a repository and a central monitoring station with seal sensors that have ultra-high sensitivity, high bandwidth, high temporal resolution, durability, configurability, scalability, and cost-effectiveness, all while providing authenticated security for the transmission of sensor data. Power for the sensor would not be required inside the repository as only the optical fiber would enter the vaults and all the active components will be emplaced at the monitoring station. Inspectors will have a real-time, remote monitoring capability that could guard against spoofing in inaccessible areas.

CONCLUSIONS

This paper has presented several concepts for monitoring the long-term containment and verification of waste containing special nuclear material in deep geological repositories. Underground repositories present new challenges for international safeguards. The principal safeguards challenges associated with both geological repositories and spent-fuel encapsulation plants include:

• Verification of spent fuel at encapsulation plant prior to transport and final emplacement
• Assuring that the waste/spent fuel is emplaced as declared
• Assuring that no waste/spent fuel is diverted before or after emplacement, including by excavating a closed and sealed repository
• Detecting such diversion or attempts in a timely manner
• Maintaining continuity of knowledge about waste/spent fuel destined for disposal and after disposal
• Verifying repository design information through remote sensing methods and underground mapping, including during concurrent construction and emplacement operations and
• Applying effective containment and surveillance (C/S) measures to canisters and to the entire Repository. [22]

Each of the techniques presented here: 1) monitoring special nuclear material in a deep geological repository via scintillating fiber optics, 2) enhanced ionizing radiation sensing with lasers, 3) distributed multi-modal fiber optic sensing, and 4) a quantum seal network, provide potential tools to enhance safeguards agreements and overcome challenges of safeguarding nuclear waste containing special nuclear material disposed of in geological repositories for as long as the safeguards agreements remains in force.

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