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ADVANCED SURVEILLANCE TECHNOLOGIES FOR USED FUEL LONG-TERM STORAGE AND TRANSPORTATION

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ABSTRACT

Utilities worldwide are using dry-cask storage systems to handle the ever-increasing number of discharged fuel assemblies from nuclear power plants. In the United States and possibly elsewhere, this trend will continue until an acceptable disposal path is established. The recent Fukushima nuclear power plant accident, specifically the events with the storage pools, may accelerate the drive to relocate more of the used fuel assemblies from pools into dry casks. Many of the newer cask systems incorporate dual-purpose (storage and transport) or multiple-purpose (storage, transport, and disposal) canister technologies. With the prospect looming for extended long term storage – possibly over multiple decades – and deferred transport, condition- and performance-based aging management of cask structures and components is now a necessity that requires immediate attention. From the standpoint of consequences, one of the greatest concerns is the rupture of a substantial number of fuel rods that would affect fuel retrievability. Used fuel cladding may become susceptible to rupture due to radial-hydride-induced embrittlement caused by water-side corrosion during the reactor operation and subsequent drying/transfer process, through early stage of storage in a dry cask, especially for high burnup fuels.

Radio frequency identification (RFID) is an automated data capture and remote-sensing technology ideally suited for monitoring sensitive assets on a long-term, continuous basis. One such system, called ARG-US, has been developed by Argonne National Laboratory for the U.S. Department of Energy's Packaging Certification Program for tracking and monitoring drums containing sensitive nuclear and radioactive materials. The ARG-US RFID system is versatile and can be readily adapted for dry-cask monitoring applications. The current built-in sensor suite consists of seal, temperature, humidity, shock, and radiation sensors. With the universal asynchronous receiver/transmitter interface in the tag, other sensors can be easily added as needed. The system can promptly generate alarms when any of the sensor thresholds are violated. For performance and compliance records, the ARG-US RFID tags incorporate nonvolatile memories for storing sensory data and history events.

Over the extended long term, to affirmatively monitor the condition of the cask interior (particularly the integrity of cover gas and fuel-rod cladding), development of enabling technologies for such monitoring would be required. These new technologies include radiation-hardened sensors, in-canister energy harvesting, and wireless means of transmitting the sensor data out of the canister/cask.

INTRODUCTION

Dry cask storage systems (DCSS), either bare or canister-based, are being used by nuclear utilities worldwide to handle the ever-increasing number of discharged fuel assemblies from nuclear power plants [1,2]. The number of casks presently in service in the United States is >1,200, and the number is projected to grow steadily beyond 2,000 by 2020 [3]. Continual surveillance of DCSS is required to ensure that the requirements of cask performance are met for public and facility safety [4]. The majority of dry casks have used welded canisters containing the used fuel assemblies, whereas a minority of dry casks used bolted closures. For these casks, post-storage transportation require removal of welded canisters or retrieval of used fuel assemblies from the dry cask and relocate them in suitable transportation overpacks. Such retrieval and reloading, either in air or in the used-fuel storage pool, requires that both the fuel rods and assemblies possess adequate structural integrity. Any canisters and casks that experienced significant degradation during extended storage may also face the need of retrieval of used fuel assemblies for a cask replacement. Because a disposal path is lacking in the United States at present, extended cask storage, up to multiple decades, may be required. Ensuring the structural integrity of the used fuel assemblies, the canisters, and other structures and components in the DCSS that are important to safety and ensuring used fuel retrievability over an extended period is imperative.

The canisters or casks are loaded under water in the used-fuel pool after the used fuel assemblies are allowed sufficient decay-heat cooling – typically more than five years after the reactor discharge. Assemblies with breached fuel rods are placed inside special containers to prevent the spread of contamination in the canister or cask. After the canister or cask is loaded, lifted off the water and drained, the lids are installed and sealed either by welding or bolting. An elaborate process of vacuum drying or forced helium dehydration is then carried out before the canister or cask is back-filled with helium. Helium is invariably used for its inertness and good heat-transfer properties. The canisters are further protected by a concrete/ steel overpack, which also serves as a radiation shield. The annulus between the storage overpack and the canister allows for natural circulation of ambient air to dissipate the decay heat from the fuel rods. Many dry storage casks are for vertical deployment, as shown in an example in Figure 1. Others have a horizontal configuration in which the used fuel canisters are inserted horizontally into the air-cooled concrete vaults. Most modern casks and canisters can hold about 24–32 pressurized water reactor (PWR) used fuel assemblies or 56–68 boiling water reactor (BWR) used fuel assemblies and weigh between 100 and 180 tons when loaded.

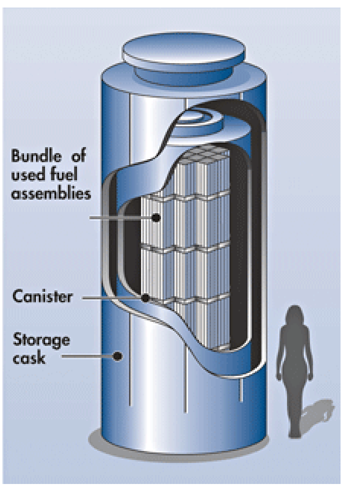

FIGURE 1. Typical vertical dry cask and installation

In the United States, federal regulation 10 CFR 72.236 [5] provides specific requirements for spent fuel storage cask approval and fabrication. These requirements include: subcriticality, radiation shielding, confinement and containment of materials, adequate heat-removal capacity without active cooling, and fuel retrievability. Maintaining sound fuel rod and assembly geometry and integrity in the cask is crucial to satisfying these requirements. Of the numerous potential cask degradation processes, aside from those caused by severe nature or man-made disasters, air/moisture ingress into the cask is possibly the one with the gravest concern. The displacement of the more-conductive helium cover gas by air/moisture would cause the canister interior temperature to rise. Air and moisture could also cause the zirconium-based fuel rod cladding to oxidize if the system temperature is sufficiently elevated. The released hydrogen from zirconium/ moisture interaction could form a combustible mixture, as well as causing further embrittlement of the cladding weakened by radial hydrides [6]. The oxidation of the UO_2 fuel through any cladding defect and the resultant volumetric increase could exacerbate the cladding breach.

Currently, the dry cask storage systems are not required to have instrumentation to monitor heat loads or radiation leaks on a continuous basis. Rather, scheduled manned surveillance ensures that the inlet and outlet vents of the dry cask storage systems remain unblocked and radiation levels normal. Additional manned inspections may be performed after unusual events, such as severe storms, earthquakes, or fire, to ensure that safe conditions are maintained. Cameras and radiometric scanners are sometimes used to supplement the routine surveillance. While these measures have been proven to be effective thus far, they may not be sufficient in the long term, particularly when fuel retrievability is an issue. To ensure performance and regulatory compliance, an autonomous and continuous monitoring system incorporating environmental sensors is imperative.

This paper describes the work supported by the U.S. Department of Energy (DOE) for the Used Fuel Disposition Campaign for R&D on very long-term storage and transportation. Under the title of advanced surveillance technologies, an existing RFID-based system, called ARG-US [7,8], is heavily leveraged as a base platform for further development of continuous monitoring capability for structure, system and components (SSC) in DCSS. There are numerous benefits of an autonomous RFID-based surveillance system for DCSS operation. By scaling back manned inspections, radiation exposure to personnel can be reduced, reinforcing the universally endorsed principle on protection against radiation — ALARA (as low as reasonably achievable). Likewise, early warnings of the degradation of the SSCs in DCSS can mitigate the consequences of an incident, thereby significantly improving safety and protection of the public and facility. Real-time access to the data on the status and history of the DCSS also greatly enhance situation awareness and operation efficiency and enhance overall cost-effectiveness of the DCSS operation.

ARG-US RFID SYSTEM

"ARG-US," meaning a watchful guardian, was developed by Argonne National Laboratory under the auspices of the DOE Packaging Certification Program (PCP), Office of Packaging and Transportation of the U.S. Department of Energy Environmental Management (DOE-EM). The system is designed to continuously monitor and track sensitive nuclear materials contained in drums during both storage and transportation. The system has been deployed at multiple DOE sites and is considered mature and commercially feasible. Figure 2 shows ARG-US tags mounted on several types of nuclear materials drums. For use in dry cask storage systems, the form factor and mounting mechanism would need to be modified, and additional sensors would need to be incorporated.

FIGURE 2. ARG-US RFID tags mounted on multiple drum types

Hardware Platform

The tags for the ARG-US RFID system are battery powered with built-in sensors for temperature, shock, humidity, seal, radiation (gamma), and battery strength. The front of the tag is a plastic chasis to facilitate radio frequency transmission, and the back is enclosed in a strong metal plate with a flange for drum attachment. Figure 3 shows the construction of an ARG-US tag. The electronic components for the ARG-US tag are compact and can be fitted inside suitable enclosures for different cask types.

For nuclear applications, adequate resistance of tag electronics to radiation damage is a necessity. In gamma irradiation tests performed with a Cs-137 source, the tags were verified to be functional at doses beyond 31 krad. For casks with a surface dose rate of 100 mR/h, this value translates to over 35 years of service. Should high dose rate be anticipated, the tag electronics can be replaced with more radiation-hardened components to meet the requirements.

The radio wave transceiver in ARG-US tags operates at 433 MHz and complies, for the most part, with the ISO 18000-7 standard [9]. This frequency is globally accepted and widely used. Of particular significance is its suitability for use near metallic objects, such as metal drums or dry cask canisters. Other components on the tag's mother board (see the central compartment in Figure 3) include nonvolatile memories, a temperature sensor, a humidity sensor, a cantilever piezoelectric shock sensor, and the circuitry for processing the signals from the piezoresistive seal sensor (not shown). The nonvolatile memories can be programmed to store encrypted user data (e.g., contents manifest), sensor data, and event histories. The carrier board for the radiation dosimeter (left compartment in Figure 3) has provisions to accept additional sensors, including external ones, through its versatile UART (universal asynchronous receiver/transmitter) interface.

Low-self-drain, high-capacity lithium-thionyl chloride ($Li\text{-}SOCl_2$) primary cells are used in the tags. To further extend battery service life, a smart battery management board is incorporated (right compartment in Figure 3). While up to four batteries may be loaded, auto-switching keeps only one battery on duty at any time. When the last battery is nearly depleted, an alert is issued to call for replacement. By using this method, up to 10 years of service life without battery change is projected under normal usage.

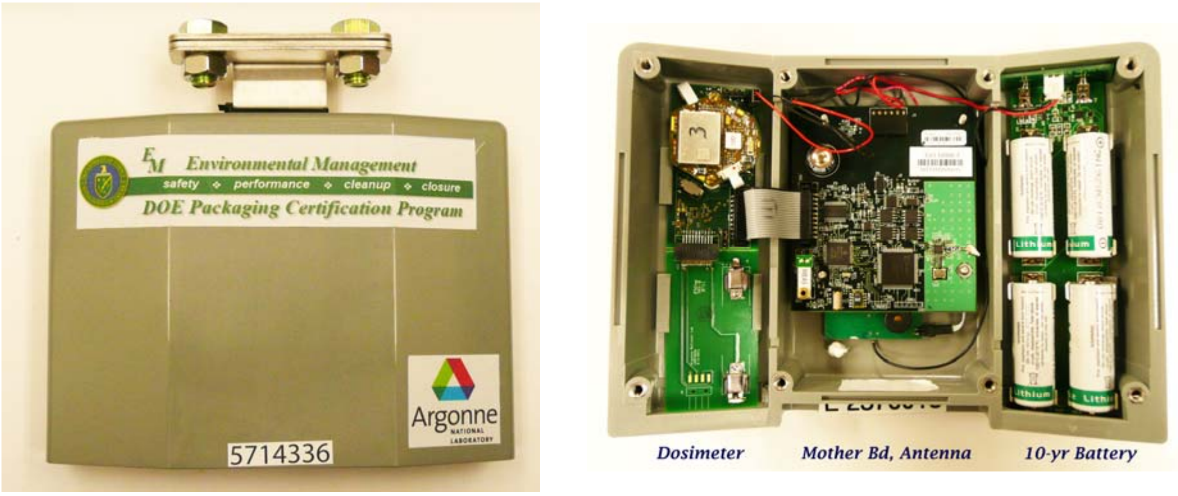

FIGURE 3. Construction of ARG-US RFID tag

To communicate with the tags via radio frequency, one or more interrogators (readers) are used. The communication is two-way – that is, the readers can receive signals from the tags, as well as send instructions to the tags. At an independent spent fuel storage installation (ISFSI), the readers may be mounted on poles or nearby structures and be connected to the control computer/database server in the command building. The read range can be >100 m and no line-of-sight is required. Mobile handheld readers may also be used if necessary.

Software Platform

Software provides the vital link between the technology and the end user and is a key component in the development and implementation of ARG-US. The ARG-US software package consists of a program called ARG-US OnSite, local and central databases, and web applications. ARG-US OnSite, the basic building block, controls the readers via the control computer and provides a graphical user interface (GUI) to operate the hardware. The design philosophy is to present all relevant information in an intuitive way on the console screen so that the user can efficiently obtain information and issue commands. In ARG-US OnSite, a user can enter or retrieve pertinent information easily with pull-down menus. With the secure Internet, information from multiple ISFSIs can be linked by using the ARG-US web applications and be accessed by authorized users anywhere and anytime.

A conceptual GUI screen of ARG-US OnSite for the DSCC application is shown in Figure 4. Each symbol represents a cask on the storage pad. The main window with a grid definition depicts the configuration of cask loading in the ISFSI. A green panel approach is adopted, in which when the status of a cask becomes abnormal, the symbol would turn to yellow (warning) or red (alert/alarm). By clicking on a symbol, detailed information on the selected cask, including the readings from all applicable sensors, is displayed in the window on the right. Panes at the bottom of the GUI screen show current status, history events, and search functions. The system can poll all tags autonomously at specified intervals or query a specific tag, as instructed by the user.

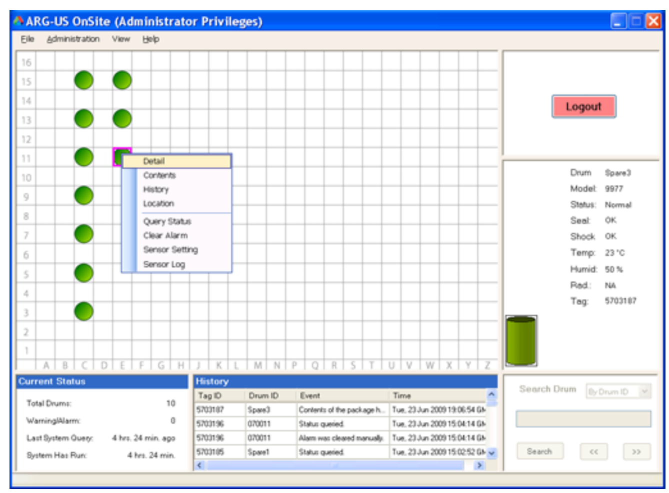

FIGURE 4. Sample screen display of ARG-US OnSite

From sub-menus of the main GUI, there are provisions for the user to enter contents manifest and processing histories, adjust alert/alarm thresholds, set auto-collect intervals, view detailed history log, and prepare data for export. The alert/alarm triggering threshold for each sensor can be set per the operating conditions. Alarm notification is instantaneous and can be promptly delivered to the responsible parties, either on-site or off-site, by multiple means.

Figure 5 shows a conceptual design of the DCSS web application for an organization operating multiple ISFSIs. By selecting the site from the right map pane, detailed information about the site, as well as the casks at that site, can then be displayed in a manner similar to that of ARG-US OnSite. Each ISFSI site can be custom modeled for its configuration and requirements.

A software quality assurance (SQA) program has been established for ARG-US. The SQA program determines the level of activities and documentation necessary for ensuring the quality of ARG-US, as well as the practices to be followed in the course of the software developmental effort. The program emphasizes design control, version control, software functionality and reliability tests, user documentation, and document control. Each version of ARG-US is tested, reviewed, and approved on the basis of the SQA program before it is released.

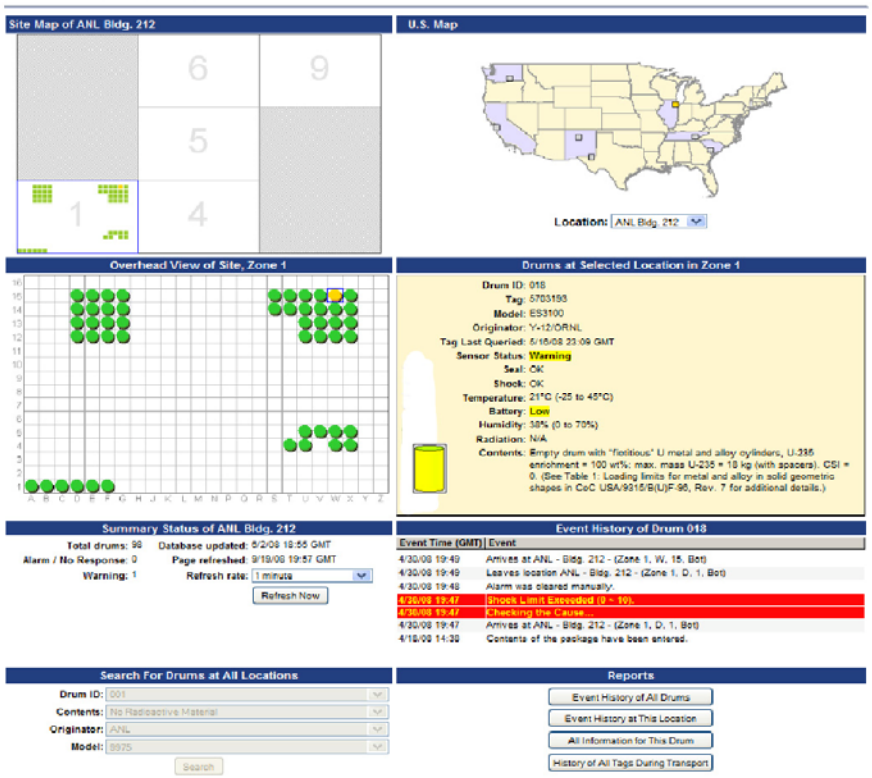

FIGURE 5. Sample web screen display of ARG-US showing multiple ISFSI sites

The functionality and performance of ARG-US OnSite and web applications have been rigorously verified in actual deployments, including transportation campaigns using Global Positioning System (GPS) tracking features.

ARG-US RFID SYSTEM FOR DCSS APPLICATIONS

With moderate modifications, the current ARG-US RFID system developed for monitoring nuclear materials drums may be used to monitor the exterior conditions of spent fuel canisters/casks. The monitoring would be autonomous and continuous, supplementing the current manned surveillance practices.

When new technologies are developed that enable the monitoring of the canister interior, such technologies may be incorporated in the ARG-US system to provide affirmative data on helium cover gas and fuel rod integrity. This ability would be particularly valuable for extended long term storage and deferred transportation of used fuel in canister/cask after storage.

Monitoring Exterior Conditions of Canister/Cask

Because of the physical bulk of casks and canisters, single sensors in the present ARG-US tags may not be sufficient to provide adequate surveillance coverage. Multiple external sensors, including digital thermometers and dosimeters, would be necessary.

There are provisions in the ARG-US tags for adding external sensors. One approach is to use the existing micro-controller unit (MCU) on the dosimeter carrier board. The MCU is capable of interfacing with many different kinds of sensors through the expansion connector. It can implement either the I2C or Serial Peripheral Interface (SPI) protocol, and additional digital bits are provided to facilitate communication with multiple sensors of the same type. By using only the I2C mode with no additional circuitry, it is possible to have up to eight temperature sensors on the basis of current commercial offerings. Expansion to significantly larger groups of temperature sensors is possible by adding additional circuitry to multiplex between groups of sensors – expansion is limited only by the physical space available for connectors and allowable power consumption. The current size of the dosimeter carrier expansion board and the current enclosure for connectors allows for up to 64 temperature sensors (8 groups of 8). Further upgrading of the tag electronics can also be implemented, if necessary.

Owing to its inertness and superior heat-transfer properties, helium is used as the cover gas in the canister, As delineated before, a loss of helium cover gas can have grave consequences for the fuel rods stored in the cask. In the absence of helium, it is conceivable that the dissipation of decay heat from the fuel rods would be affected and result in a different temperature distribution on the canister surfaces. Abe and Matsunaga [10] suggested the use of this phenomenon to correlate the condition of the helium cover gas within the canister. Takeda et al. [11] subsequently confirmed the validity of this approach with experiments. They verified that the temperature change between the top and bottom of the canister, for instance, can be readily measurable – up to 8°C in their experiments. Therefore, for the near term and before the more demanding in-canister measurement techniques are developed, using this indirect method to gauge the condition of the helium cover gas in a canister appears to be feasible. By deploying multiple thermometers over the canister surfaces, the technique may also be an effective alternative to, or supplement for, the manned inspections of the cask inlet and outlet vents – vent inspection is an important part of the current surveillance program to ensure that the vents are not blocked by foreign objects, such as leaves and debris. Reducing the needs of manned vent inspections can significantly improve worker safety and reduce personnel radiation exposure.

Similarly, multiple external radiation detectors may be incorporated in the RFID tags to monitor the radiation level at various external locations of the cask. Significant alteration of the dose profile could indicate a change in the fuel column configuration and the integrity of the fuel assemblies in the canister. Since the radiation detectors may be planted in the annulus between the canister and the concrete/steel overpack, the measurement results would be more sensitive and direct than those presently obtained from the manned surveillance over the cask surfaces. Automating the radiation survey with ARG-US RFID, similar to that for vent inspection, can enhance safety, efficiency and ALARA.

Monitoring Interior Conditions of Canister/Cask

While casks are shown in tests to meet the stringent regulatory requirements under storage and accident transport conditions, the integrity of the used fuel rods in the cask is not assured in such tests. In-canister sensors have the potential of providing this missing link with confidence. Such information is of particular value before and after deferred canister/cask transportation campaigns.

To perform in-canister monitoring, numerous enabling technologies have to be developed. The principal ones include:

- Developing sensors and components compatible with the canister's hostile environment of elevated temperatures (>200°C) and high radiation (>1,000 Rad/h),
- Powering the sensors and components beyond the typical battery life span (10 years), and
- Transmitting the sensor information wirelessly out of the canister structure.

Among the in-canister sensors, pressure transducers, humidity gauges, and Kr-85 detectors are possibly the most meaningful. Data on pressure and humidity inside the canister would provide clear evidence on the leak-tightness of the canister, and data on Kr-85 would provide unequivocal confirmation of fuel-rod integrity. (Kr-85 is a high-yield, long-life fission product gas and is not expected in the canister cover gas unless there are cladding breaches.) If Kr-85 is detected, it may be possible to correlate the level of activity with the severity or number of fuel-rod breaches. This information would be important from the standpoint of fuel retrievability. Digital thermometers may also be deployed in the canister to supplement the monitoring data described above. All instrumentation in-canister/cask should be low-power-consumption devices that can stay dormant, except during the brief period of scheduled measurements. Of course, the sensor equipment should be sufficiently heat-resistant and radiation-hardened for the intended period of services. Shielding may be used to block the intense radiation directly from the fuel rods.

To power the in-canister sensor instruments, in-situ energy harvesting and storage will be necessary. Of the commonly available energy-harvesting methods – electrodynamic (motion), piezoelectric (vibration), thermoelectric (temperature differential), and photovoltaic (photon capture) – the latter two appear to be more promising. With the thermoelectric method, solid-state devices utilizing the heat flow from the hot reservoir (canister interior) to the cold reservoir (canister exterior) need to be developed. A possible complication is to utilize the temperature gradient over the canister wall without compromising its structural integrity. With the photovoltaic method, the task is to develop devices to capture the radiation energy from the gamma rays in a manner similar to that for a conventional solar cell. Advanced Cd-Zn-Te materials that can be made into compact radiation detectors may be candidates for the construction of photovoltaic cells for in-canister applications.

Possibly the greatest challenge for in-canister monitoring is to produce a means to transmit the sensor signals through the canister wall to an outside interrogator. As there are no direct penetrations in the canister, a cable is not possible and a wireless approach has to be adopted. Among the possibilities, ultrasonic communication and magnetic inductive coupling appear to be more feasible. In the ultrasonic method, a continuous wave carrier signal may be generated outside, and the canister sensor output, encoded and modulated, may be detected as a reflected pulse and received through the wall. In one such experiment, signals were successfully collected through a 152-mm (6-in.) -thick steel wall [12, 13]. With magnetic induction, transmitting and receiving coils of proper construction have been shown to communicate via the flux lines in the magnetic field through a 22-mm-thick piece of stainless steel [14]. With either approach, the difficulty is compounded by the fact that the canister walls are often not monolithic. Additional experimental and modeling effort will be required to address the layered wall construction.

DISCUSSION

High-burnup fuel issues [15] and managing aging effects on used fuel dry cask systems [16] for extended long-term storage and transportation are two other areas where Argonne is participating in the DOE Used Fuel Disposition Campaign for R&D on storage and transportation. Two generic aging management programs are being developed: one for welded canister seal and leakage monitoring and the other for bolted cask seal and leakage monitoring. Both existing and advanced surveillance technologies are leveraged for the development of capabilities for remote, continuous monitoring of the functional and structural integrity of the used fuel canisters, as well as other structure, system and components that are deemed important to safety for dry cask storage systems. Integrity of canisters/casks and that of the used fuel rods in them are vital for the safe operation of DCSS during long-term storage and transportation.

While research is underway to study drying/transfer conditions that could mitigate radial-hydride-induced cladding embrittlement for high-burnup fuels [15], there is presently insufficient data to confidently project rod integrity beyond even the short term. One of the key performance metrics for safe DCSS operation during long-term storage and transportation is to maintain the helium cover gas, as it impacts both the thermal and degradation processes of the rod cladding in the canister or cask. While in-canister and in-cask monitoring is desirable as it can verify the actual conditions of used fuel rods, it may be difficult to implement in the near term. While the necessary enabling technologies are being developed, it may be feasible to perform canister/cask monitoring now with a modern RFID-based surveillance system such as ARG-US. With multiple sensors monitoring the external surfaces of the canister, indications on helium cover gas and fuel column integrity may be obtained. The data thus collected on an autonomous and continuous basis can also enhance the efficiency of on-going surveillance effort and improve the cost-effectiveness and ALARA implementation for the ISFSI operations.

SUMMARY

The integrity of canisters/casks and that of the used fuel rods in them are vital for the safe operation of DCSS during extended long-term storage and deferred transportation. The present surveillance programs, while adequate for near-term storage, may not be sufficient for extended long term storage, which can span multiple decades. Likewise, present practices do not ensure the integrity of the used fuel rods in the canister/casks. A modern, automated RFID-based surveillance system, such as ARG-US with remote sensors on the canister surfaces, may be used to supplement the current surveillance programs. As monitoring with ARG-US RFID is both comprehensive and continuous and requires minimal operator participation, improvements in safety, ALARA, and cost-effectiveness can be expected. When enabling technologies for in-canister monitoring are developed, they can be incorporated with ARG-US to affirmatively monitor the two most important parameters of safe storage and transportation – condition of helium cover gas and integrity of fuel-rod cladding in the canister/cask.

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REFERENCES

1. United States Department of Energy, Office of Nuclear Energy, "Fuel Cycle Research and Implementation Plan, Office of Nuclear Energy, Washington, D.C., 2010.
2. International Atomic Energy Agency, "Long term Storage of Spent Nuclear Fuel – Survey and Recommendations," IAEA-TECDOC-1293, Vienna, 2002.
3. United States Nuclear Waste Technical Review Board, "Evaluation of the Technical Basis for Extended Dry

Storage and Transportation of Used Nuclear Fuel," December 2010.

4. United States Nuclear Regulatory Commission, "Standard Review Plan for Spent Fuel Dry Storage Systems at a General License Facility. Draft Report for Comment," NUREG-1536 Rev. 1A, 2009.
5. United States Nuclear Regulatory Commission, Title 10, *Code of Federal Regulations*, Part 72, "Energy: Licensing Requirements for the Independent Storage of Spent Nuclear Fuel and High-Level Radioactive Waste, and Reactor-Related Greater than Class C Waste," Washington, D.C.: Office of Federal Register National Archives and Records Administration, U.S. Government Printing Office, as amended June 9, 2008 (10 CFR 72).
6. Daum, R., et al., "Radial-hydride Embrittlement of High-burnup Zircaloy-4 Fuel Cladding," Journal of Nuclear Science and Technology, Vol. 43, 2006, pp. 1054–1067.
7. Tsai, H., et al., "Applying RFID Technology in Nuclear Materials Management," Packaging, Transport, Storage & Security of Radioactive Material, Vol. 19, No. 1, 2008.
8. Chen, K., Tsai, H., and Liu, Y., "Development of the RFID System for Nuclear Material Management," Proceedings of the Institute of Nuclear Materials Management (INMM) 49th Annual Meeting, Nashville, TN, July 2008.
9. International Organization for Standardization, ISO/IEC 18000-7:2009.
10. Abe, I., and Matsunaga, K., Japan Patent Office P2002-202400A, 2002.
11. Takeda, H., et al., **"**Development of the Detecting Method of Helium Gas Leak from Canister," Nuclear Engineering and Design, Vol. 238, Issue 5, May 2008, pp. 1220–1226.
12. Murphy, T. L., "Ultrasonic Digital Communication System for a Steel Wall Multipath Channel: Methods and Results," LM-06K004, February 16, 2006.
13. Saulnier, G. J., et al., "Through-Wall Communication of Low-Rate Digital Data Using Ultrasound," IEEE Ultrasonic Symposium 2006, Oct. 2–6, 2006, pp. 1385–1389.
14. Wilhelm, G. R., and Jaskolski, C., "Magnetic Communication through Metal Barriers," U.S. Patent Application US 2008/0070499 A1, March 20, 2008.
15. Billone, M., Liu, Y., Nutt, M. and Sorenson, K., "High Burnup Fuel Issues for Long-Term Dry Cask Storage and Transportation," Proc. ICEM 2011, Reims, France, September 25-29, 2011.
16. Chopra, O., Diercks, D., Ma, D., Shah, V., Tam, S., Fabian, R., Liu Y. and Nutt, M., "Managing Aging Effects on Used Fuel Dry Casks for Long-Term Storage," Proc. ICEM 2011, Reims, France, September 25-29, 2011