Title: Multi-Sensor Inspection and Robotic Systems for Dry Storage Casks

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ABSTRACT:
The increased reliance on interim dry storage of used nuclear fuel in the U.S. nuclear power industry and the unavailability of a final disposal repository raises questions about the long-term performance and possible degradation of dry storage systems. Environmentally assisted cracking (EAC) of the stainless steel canister and degradation of the concrete overpack are viewed as the primary limitations to the longevity of the dry storage cask. The monitoring of possible degradation agents and modes is necessary to ensure the continued health of these systems. However, many of the locations inside the storage cask that are of greatest interest for monitoring are difficult to access and have associated hazards making sensor delivery an enormous challenge.

The *technical merit* of our proposed research includes: novel in-situ surface composition characterization, nondestructive inspection methods appropriate for the canister using linear and nonlinear ultrasonic guided waves, ultrasonic nondestructive inspection of bare and clad concrete, and development of a robotically guided wand for access to a harsh and hazardous environment within confined spaces that also provides sensor positional awareness. The team's *proposed approach* to develop sensing capabilities and robotic delivery in a stepwise progression by addressing fundamental issues, laboratory trials, benchmarking, field trials, and then final prototype integration provides excellent flexibility and the best opportunity for success. *Each investigator* is a proven leader in their task areas associated with this project, has the facilities necessary to be successful, and will be guided by an advisory board experienced in dry storage of used nuclear fuel. Further, the PI has served in that role on previous NEUP projects. The *budget* supports seven professors and eight graduate students at three different universities in three states. It supports the development of sensing systems and robotics at a ratio of roughly 3 to 2. It also enables advisory board meetings, prototype testing at partner facilities, and research experience for undergraduates that will enhance participation of under-represented groups.

Specifically, this research proposes a robotic device and new sensing systems to monitor for conditions conducive to EAC and inspect for cracks within dry storage casks. The sensor insertion device – a robotically guided wand system – will be designed specifically to provide access to the canister surface through the ventilation system of the overpack for both horizontal and vertical storage systems. The robotic system will enable a broad range of measurements to be made through a common, multi-sensor interface. At the same time, new characterization and inspection methods will be developed to meet the unique demands of dry storage systems. The spectrum of sensing modalities and functionality include:

- Surface sampling – laser induced breakdown spectroscopy (LIBS) and Raman spectroscopy delivered by optical fiber as well as debris collection (e.g., dust, salts, reaction products) for laboratory analysis;
- Nondestructive inspection – linear and nonlinear ultrasonics using noncontact electromagnetic acoustic transducers (EMATs) for the stainless steel canister, ultrasonic surface waves for the concrete overpack, as well as video (to identify bolt corrosion for example), thermal imaging (thermography), and Lidar/UT for dimensional metrology;
- Environmental sensing – temperature, relative humidity, ionizing radiation (to assess seal integrity and provide operational environment awareness).

Modeling will be conducted to predict the environment in which the measurements will be made, and its evolution, with respect to radiation and temperature. Not only will this modeling be valuable for designing durable delivery and sensing systems, but it is also necessary to interpret the results of the measurements.

A guided wand robotic system that supports a multifunctional sensor suite will be developed to provide accessibility for evaluating the condition of dry storage casks. Access to the interior will be through the ventilation system of the overpack. Highlights of the guided wand system are: 35' reach, motorized end effector with both electro-mechanical and air-articulated guidance, vacuum enabled fixtures to maintain positioning, and universal adapters for mounting various types of sensing systems. The guided wand will be capable of navigating around multiple 90-degree corners in the ventilation system to provide thorough coverage of the canister. It will have a sufficiently small cross section to fit into very confined spaces (as small as 2"x8") as well as be functional in open unconstrained spaces, and be designed so that passive removal of the probe is possible in the case of faults in the robotic actuation. *The use of a wand insertion system allows power, data storage, and guidance systems to be located outside the cask, thus greatly simplifying the system and allowing significantly smaller components*.

The guided wand will deliver the sensor suite to assess how conducive the environment inside the overpack is to EAC. LIBS and Raman spectroscopy systems will be *delivered via an optical fiber* for elemental analysis of surface samples from the canister and the inside of the overpack. Compact EMATs will be developed to perform nondestructive inspection for EAC and precursors to EAC, using guided ultrasonic waves that provide unprecedented access to obstructed areas. EMATs, in addition to being noncontact transducers, provide the flexibility to use shear-horizontal, Lamb, or Rayleigh waves to inspect for cracks. In addition, *nonlinear ultrasonics can be employed to detect subtle microstructural changes* that precede EAC. Both LIBS and EMAT sensing systems will be benchmarked with respect to state of the art systems.

Overpack concrete degradation will be assessed using a separate surface scanning robotic system for exterior surface scanning using air-coupled piezoelectric transducers that generate ultrasonic surface waves from a moving test platform on both bare and clad concrete surfaces. Special attention will be paid to assess concrete in the vicinity of vents and connectors where degradation is most likely to occur owing to enhanced moisture ingress.

Operation of the guided wand system and its ability to deliver a multifunctional sensing system will be demonstrated in a mock-up storage system provided by our partners. Due care and consideration will be given to both the operational environment and data management with respect to security. The ability to monitor and inspect inside a dry storage cask that this project will provide enables both safe interim storage of nuclear waste and a means to justify recertification of storage systems. Commercial systems should follow from this groundbreaking project.

A team of researchers, whose combined areas of expertise uniquely address the relevant challenges, will conduct the project. From Penn State: Cliff Lissenden will lead and manage the project as well as be responsible for nondestructive inspection of the canister, Arthur Motta will serve as co-director of the project and head the integration efforts, Igor Jovanovic will lead surface composition measurements, Sean Brennan will lead robotic system development, and Karl Reichard will be responsible for data management and security. John Popovics from the University of Illinois will be responsible for nondestructive inspection of concrete, while Travis Knight from the University of South Carolina will model conditions inside storage casks. Huidong Gao, from Innerspec, will design and fabricate EMATs. An advisory board of industry experts provides input, feedback, and facilitates dissemination of results: John Wagner and Dwight Clayton – ORNL; Harold Adkins and Ryan Meyer – PNNL; John Kessler – EPRI; Laszlo Zsidai – Holtec International.