



Performance Requirements for Remote Sensors in Spent Fuel Operations

**Summary of Stakeholder Inputs on Dry Canister Storage,
Transportation and Disposal**

2021 TECHNICAL REPORT



PORTIONS
TRANSLATED

Performance Requirements for Remote Sensors in Spent Fuel Operations

Summary of Stakeholder Inputs on Dry Canister Storage, Transportation and Disposal

All or a portion of the requirements of the EPRI Nuclear
Quality Assurance Program apply to this product.

YES



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Abstract

EPRI is working cooperatively with the U.S. Department of Energy (DOE), U.S. Nuclear Regulatory Commission (NRC), Nuclear Energy Institute (NEI), and domestic and international utilities, national laboratories, dry storage vendors, and research and development organizations to improve knowledge related to the internal environment of dry storage systems. One approach identified in this work is the potential opportunity to enable the use of sensors in locations with extreme radioactive environments to measure environmental parameters such as peak cladding temperature. If successful, these sensors could be used in a variety of potential applications where direct measurements could be useful in extreme environments such as high-level waste tanks, deep geologic repositories, etc.

This report summarizes activities performed in support of developing the performance requirements that might be expected of sensors used in highly radioactive environments, with a focus on different aspects of the spent fuel lifecycle (i.e., storage, transportation, and disposal). EPRI hosted and facilitated a workshop with subject matter experts from the DOE, NRC, national laboratories, domestic and international utilities, dry storage vendors, and other R&D organizations related to the performance requirements expected from sensors for back-end operations. In addition, a survey questionnaire on desired sensor attributes and performance was also developed for the subject matter experts, and the responses were gathered and are summarized in this report.

Keywords

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KEY RESEARCH QUESTION

The use of sensors in spent fuel storage applications has been identified as a way to enable opportunities for a more balanced approach to spent fuel. By reducing certain margins while ensuring the public health and safety is maintained and reducing worker dose, an overall increase in safety can be achieved. This report summarizes initial information-gathering exercises used to define performance requirements for sensors in spent fuel storage applications.

RESEARCH OVERVIEW

An initial step in defining the desired performance characteristics for the types of sensors that might be used for spent fuel storage included a two-day workshop on sensors for spent fuel operations. The presenters and the attendees were stakeholders from various areas of spent fuel management, including storage, transportation, and disposal. The workshop was used to introduce a survey designed to elicit stakeholder input related to sensor attributes and performance characteristics. This report summarizes the results of the workshop and the survey.

KEY FINDINGS

- The temperature of the cask/canister internal environment is strongly supported as an attribute of interest for use in casks/canisters under Storage Operations, Transport Operations, and Disposal Operations.
- If sensors are to be used that are internal to the cask/canister, the strongly supported method of data transmission is a wireless remote method.
- Some stakeholders expressed the view that sensors are best used as information-only. However, other stakeholders noted that the cost of implementing sensors would generally be expected to be offset by reductions in regulatory burden. For this to occur, sensors would need to take on a safety-related role.
- Many stakeholders noted that the reliability requirements of sensors increase substantially if the sensors will be used for licensing or regulatory benefit.

WHY THIS MATTERS

By defining the attributes and uses for sensors that are desired by stakeholders of spent fuel operations, research can be focused on developing sensors that meet these use cases.

HOW TO APPLY RESULTS

The spent fuel storage sensor performance requirements discussed during the workshop and elicited in the stakeholder survey can be used to focus future research for spent fuel sensor implementation.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- This work presents the views of a variety of nuclear stakeholders, including industry members, EPRI, the U.S. Department of Energy, multiple U.S. national laboratories, equipment developers, and system vendors. Opportunities for learning and engagement among these entities are promoted by EPRI during the bi-annual meetings of the Extended Storage Collaboration Program (ESCP).

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Table of Contents

Abstract	V
Executive Summary.....	VII
Section 1: Introduction	1-1
Background	1-1
Approach	1-2
Section 2: Canister Workshop Summary.....	2-1
Workshop Agenda	2-1
Summary of Presentations and Discussion	2-1
High-Burnup Demonstration Cask Thermocouples	2-2
Sensor Options and Lessons Learned for HBU Demo	2-3
Industry Perspective for Sensors	2-3
X-Wave Innovations Canister Internal Sensors	2-4
IAEA Perspectives on Sensors.....	2-5
Westinghouse Sensor Development	2-6
DOE Transportation Tests	2-7
SKB Perspective	2-8
UK Nuclear AMRC – Challenges of Monitoring Long-term Storage.....	2-8
Section 3: Canister Sensors Requirements Survey Summary	3-1
Page 1: Respondent Information	3-1
Question 1: Contact Information	3-1
Question 2: Stakeholder Area of Interest	3-1
Page 2: Sensor Attributes	3-2
Question 3: Key Attributes	3-2
Question 4: Internal vs External Sensors.....	3-2
Question 5: Remote vs Wired Internal Sensors.....	3-3
Page 3: Remote Sensors.....	3-3
Question 6: Sensor Lifetime	3-3
Question 7: Environmental Qualification.....	3-3

Question 8: Remote Data Collection (Sensing, Transmission, and Receiving Options)	3-4
Page 4: Implementation of Sensors	3-4
Question 9: Single vs Multiple Sensors.....	3-4
Question 10: Sensor Reliability	3-5
Question 11: Sensor Reliability over Time.....	3-5
Question 12: Distribution of Sensor(s) and Sampling	3-6
Question 13: Location of Sensor(s).....	3-6
Question 14: Effects Considerations.....	3-7
Page 5: Additional Considerations.....	3-7
Question 15: Potential Benefits of Sensors	3-8
Question 16: Potential Risks of Sensor Implementation	3-8
Question 17: Other Applications.....	3-9

Section 4: Conclusions.....4-1

Appendix A: Translated Table of Contents..... A-1

繁體中文 (Chinese – Traditional)	A-2
日本語 (Japanese).....	A-6
한국어 (Korean)	A-10
Español (Spanish).....	A-14



Section 1: Introduction

Background

EPRI is working cooperatively with the U.S. Department of Energy (DOE), U.S. Nuclear Regulatory Commission (NRC), Nuclear Energy Institute (NEI), and domestic and international utilities, national laboratories, dry storage vendors, and research and development organizations to benchmark thermal models used to ensure spent fuel integrity. Regulatory guidance identifies the need to maintain the maximum cladding temperature experienced by loaded spent fuel into Dry Cask Storage System (DCSS) canisters to remain below 400°C during short-term loading operations, storage, and transportation. Thermal analyses using computational fluid dynamics (CFD) are frequently performed to ensure the peak cladding temperature remains below the regulatory limit. Currently, design licensing basis thermal models use bounding assumptions and engineering margins to account for various uncertainties in the data and analysis methodology. This approach could lead to longer than necessary fuel cooling times in spent fuel pools, reduced capacity of dry storage systems, and could introduce operational limitations preventing measures to further reduce worker doses. Moreover, bounding approaches could lead models to overpredict external wall temperatures, resulting in potentially non-conservative corrosion initiation estimates.

To examine this issue, EPRI initiated a blind round-robin research project comparing analytical CFD thermal analyses to actual measurements from the High Burnup (HBU) Fuel Demonstration Project. The results indicate that the bounding assumptions used in design licensing basis thermal models significantly bias the results to the high side. These results significantly reduce the concerns for the potential embrittling effects of hydride reorientation in HBU fuel during short-term operations and dry storage since temperatures were found to be lower than predicted and much lower than the 400°C regulatory limit. Furthermore, this project identified potential benefits associated with more accurate thermal models to include:

- More efficient loading which translates into fewer casks loaded,
- Shorter minimum required cooling times enabling shorter decommissioning timeframes
- Improved operational flexibilities that could reduce worker doses by allowing additional shielding blankets to be emplaced during loadings

- Additional fuel loading patterns to accommodate more diverse fuel assemblies like higher burnup fuel leading to additional loading flexibilities, and
- More efficient repository designs and footprints, leading to significant savings and more efficient use of costly geologic repositories

As a follow-on activity to the thermal modeling project, subject matter experts from the NRC, DOE, national laboratories, EPRI, vendors, and utilities participated in an expert elicitation using the Phenomena Identification and Ranking Table (PIRT) process to identify, quantify and rank the uncertainties for thermal modeling and regulatory limits on fuel performance during storage operations. Regulators have used this process in the past to provide them with an independent expert assessment to support their decision-making, and any technology and/or methodology developments that could further focus research and development needs such as additional testing or model benchmarking. This process has been shown to be an effective tool to accelerate the integration of new methodologies and advanced technologies in the nuclear industry.

The PIRTs evaluated the performance margins and enabled potential opportunities for a more balanced approach by reducing certain margins but ensuring the public health and safety is maintained while reducing worker doses which increases overall safety. Another approach identified in the Thermal Modeling PIRT was the potential opportunity to enable the use of sensors in locations with extreme radioactive environments. The idea is to use measurements in lieu of modeling to show that licensees meet the peak cladding regulatory limits of 400°C for spent fuel. If successful, these sensors could be used in a variety of potential applications where direct measurements could be useful in extreme environments such as high-level waste tanks, deep geologic repositories, etc.

Approach

A broad approach was taken to define the desired performance characteristics for the types of sensors that might be used in the extreme radiation environments typified by spent fuel storage.

The first step in this approach was to plan, host, and facilitate a two-day workshop on sensors for spent fuel operations. The presenters and the attendees were stakeholders from various areas of spent fuel management, including storage, transportation, and disposal. The workshop participation was international, with attendees from multiple countries. Presentations were given providing multiple perspectives on potential uses of sensors, including those from: 1) research institutions, 2) national laboratories, 3) equipment developers, and 4) industry members.

The workshop was also used to introduce a survey questionnaire that covers aspects of sensor performance. The attendees of the workshop were invited to participate in the survey, with a goal of gathering desired sensor characteristics from a broad representation of stakeholder within the spent fuel community.

The presentations and video recordings from the Workshop on Sensors for Spent Nuclear Fuel Operations can be downloaded from this URL:

<https://epri.app.box.com/folder/128055876838?s=kfu4fyupp8v8dk7v95jxp9fmedl8847h>



Section 2: Canister Workshop Summary

In December 2020, a two-day workshop was held on the topic of using sensors in spent fuel operations. The purpose of the workshop was to begin a process that will accelerate the development and qualification of remote wireless sensors for spent nuclear fuel operations. The workshop included presentations related to remote sensor applications in spent fuel operations and sought to generate stakeholder input on items such as key attributes/benefits, functional criteria, and survivability/reliability of sensors in spent fuel operations. These concepts were explored across the range of spent fuel operations, defined as Dry Storage (i.e., at a site), Transportation, and Disposal.

Workshop Agenda

The following presentations were given during the workshop:

- High-Burnup Demonstration (HBU Demo) Cask Thermocouples: Benefits and Challenges of Wired Thermal Sensors
- Sensor Options and Lessons Learned for the EPRI/DOE High-Burnup Demonstration Cask
- U.S. Industry Perspectives on Cask Sensors
- Development of a Sensor System for Long-Term Remote Monitoring of Internal Conditions of NUHOMS 32TPTH Canisters
- Non-Intrusive Temperature and Pressure Wireless Sensor and Transceiver System for Spent Fuel Assemblies in Dry Storage Casks
- IAEA Activities to Include Sensor Developments
- SNF Transportation Triathlon: DOE International Multi-Modal Surrogate Spent Fuel Transportation Test
- SKB Perspectives on Sensors for Spent Fuel Operations
- Challenges of Monitoring Long-term Nuclear Waste Storage

Summary of Presentations and Discussion

The following is a summary of each presentation from the workshop along with topics related to sensors that were covered during the discussion.

High-Burnup Demonstration Cask Thermocouples

Discussion during the presentation included:

- Measurements were desired for: 1) internal temperature measurement, 2) external temperature measurement, 3) internal gas sampling, and 4) internal pressure
- Wireless sensors were not selected for the HBU Demo cask due to: 1) licensing risk, and 2) the time required to qualify the sensors.
- While designing the thermocouple lances, one significant challenge was needing to consider dimensional tolerances and slack in defining the lance locations.
- There was an operational risk that the cask would fail leak test that increased with each thermocouple seal that was added.
- The recommendation from the experience is to install sensors on the inside of the confinement before loading, and take readings without wires.

Questions and comments during the presentation related to sensors included:

- **Comment:** If the HBU Demo cask were for a longer-term initiative, we should not preclude the use of sealed penetrations. My experience is that wireless sensors will be difficult to implement in a cask system.
Response: Agreed
- **Question:** Can you discuss how penetrations affect eventual transportation?
Response: An analysis was needed to demonstrate that the penetrations wouldn't slide during transportation. The side-drop case was limiting.
- **Question:** What is the expected lifetime for these thermocouples?
Response: Ten to twenty years
- **Question:** Do you think you'll need regular instrumentation of licensed storage casks in the future? **Response:** We need to develop the capability and we need to be smart about what we'll require of the instrumentation (e.g., validation efforts or data on hundreds of casks). We need to consider using measurements of the internal environment, instead of relying on models.
- **Question:** What parameters do you think would need to be measured over long durations? **Response:** Temperature is one, gas composition is another. Gas composition could demonstrate helium is still present in the case of a through-wall crack.
- **Question:** Were the thermocouples tested under high radiation conditions? **Response:** Yes, they are the same as used inside the reactor. The utility pushed for off-the-shelf and qualified components.
- **Question:** Could thermocouple penetrations used for the bolted cask be used in a welded canister? **Response:** Thermocouple lances in a welded canister system would be more difficult because there is much more limited space between the canister and the overpack/cask. It could be done, but would require more design effort to reduce the size of the external package.

Sensor Options and Lessons Learned for HBU Demo

Discussion during the presentation included:

- Design challenges: it was very important that the hardware must be compatible with the design constraints of the candidate storage cask; corrosion, environment, etc. compatibility
- Meeting with the NRC demonstrated they did not want penetrations. Thermocouple lances were okay, but nothing else and they needed an already-qualified penetration. The potential for loss of confinement was paramount to the NRC. Additionally, because you can't open the cask, there can be nothing inside the cask that can affect the contents and nothing that can break during transport.
- Design concepts that were rejected included:
 - Sample bottles at the top – risk to confinement integrity
 - Sample bottles in the cask – risk to internals
 - External sensors – considered unproven at the time (2014)
 - Instrument well – confinement risk
 - Sapphire window – could break in topper

Questions and comments during the presentation related to sensors included:

- **Comment:** The discussions with the NRC related to risks to confinement integrity highlights the fact that any design needs to meet the criteria set forth in regulations and associated guidance.
- **Question:** Please provide more information about the concern from the regulator related to sensors breaking and internals. **Response:** Internal sensors with batteries inside the canister was a “bridge too far” for the regulators to accept at the time. The concerns about the external penetrations and the sensors breaking was related to loss of confinement.

Industry Perspective for Sensors

Discussion during the presentation included:

- Advantages to using sensors include:
 - Allow additional fuel to be loaded sooner, due to known temperatures
 - Reduce restrictions during loading operations (time limits, 3-day rolling temperature recording)
 - Providing “true” temperatures may help with aging management evaluations of canisters and canister materials

- Challenges to using sensors include:
 - New technical specification could lead to licensing and compensatory measures requirements
 - Additional equipment could result in additional preventative and/or routine maintenance requirements, spare parts, and procedures
 - Questions about whether the technology will become obsolete, with parts unavailable or not supported by the vendor
 - Concerns about reliability for sensors, considering the challenges of the ISFSI external environment (wind, snow, rain, extremes of high and low temperatures including solar insolation).
 - Concerns about data retrieval and what evaluations will be required for the data. Additional site resources and/or equipment may be required for the sensors.
- The benefits of sensors will need to be more significant than what's been shown so far by the HBU Demo thermocouples due to the challenges associated with implementation.

Questions and comments during the presentation related to sensors included:

- **Question:** Could the additional data provided by sensors improve public confidence in spent fuel storage? **Response:** It is better to do what is technically correct; the additional information may or may not improve public confidence.
- **Question:** Why would there be additional Tech Specs imposed on remote sensors for dry storage operations, if there were no change to the operations themselves? Wouldn't there have to be some kind of change? **Response:** The cask designer will need to identify the licensing strategy they pursue if sensors are used.

X-Wave Innovations Canister Internal Sensors

Discussion during the presentation included:

- System consists of Surface Acoustic Wave (SAW) sensors and Bulk Acoustic Wave (BAW) transducers
- SAW sensors used to measure values of interest, including: 1) temperature, 2) pressure, 3) relative humidity, and 4) hydrogen gas concentration.
- BAW transducers used for wireless acoustic communications from inside the canister to outside the canister.
- Changes in measurement variables result in changes to the acoustic wave that are detected by the SAW

- SAW sensors feature high temperature and pressure operation, perform well after water submersion and vacuum drying, and saw no performance degradation after 2,400 Gy gamma irradiation.
- Also working on thermoelectric harvester to use canister heat differential from interior to shell as a means of generating energy.

Questions and comments during the presentation related to sensors included:

- **Question:** Does the system store data that can then be sent to the exterior, so that you get a lot of data in a single data dump? **Response:** For the thermoelectric powered sensor, no. However, you can collect data over time on an external system. You can also design an externally powered system that powers up only when you want to capture data.

IAEA Perspectives on Sensors

Discussion during the presentation included:

- IAEA Coordinated Research Projects (CRPs) bring together research institutes to collaborate on research topics of common interest. Project duration is around 3-5 years.
- New CRP to start in 2022 on aging management programs for dry storage systems focusing on behavior/performance of spent fuel storage systems. This CRP has the possibility to include sensor development for storage system monitoring.
- Personal Opinion (not IAEA position) on considerations for sensors in dry storage systems
 - It is expected that the sensor lifetime will be below storage duration
 - There should be no dependency on an active component
 - Internal condition monitoring should not be designated as an essential safety feature. Instead, it should be considered an add-on to provide supporting information.
- Personal Opinion (not IAEA position) on a wish list for sensors in dry storage systems
 - Wireless data transmission (no penetrations)
 - Lifetime of up to 40 years is desirable
 - Sensor data of interest: humidity, temperature, pressure, gas composition measurement
 - Continuous online reading is preferred to permit trend identification
 - Self-surveillance functions to indicate a sensor defect

- Personal Opinion (not IAEA position) on regulatory aspects for sensors in dry storage systems
 - Sensor material should be already used in nuclear applications with a similar high radiation environment, with a known aging behavior
 - The sensor should be classified as not related to safety

Questions and comments during the presentation related to sensors included:

- **Question:** What is your basis for selecting a desired 40-year lifespan for sensors? **Response:** It is based on a 40-year license interval, not technical.
- **Comment:** Temperature data for the first two weeks could be used for regulatory compliance, and data after that time period could be informational.
- **Comment:** I see no need for sensor data for regulatory compliance, either in the current framework or any reasonable future framework. Sensor data may be appropriate for long-term confirmatory issues, but leave them out of Tech Specs. They are not needed to provide reasonable assurance of adequate protection.
- **Question:** Could replaceable external sensors be relied on as part of a safety case? **Response:** If they can be easily (low dose) replaced, then it could be better. A key issue is can you reliably detect information of interest from the outside of the canister.
- **Comment:** I feel it is important to keep the required technology passive. Given technology advancements, sensors can be added to help us gain data on the ageing health of the casks/canisters, but we should not put ourselves in the position of requiring these sensors in systems. The sensors should be an added optional safety measure.
- **Comment:** Perhaps we should have a discussion about whether sensors should/could be used for anything beyond R&D, specifically regulatory compliance.
- **Comment:** There is an NRC report on monitoring: Available Methods for Functional Monitoring Dry Storage Systems, Accession No. ML14323A067.

Westinghouse Sensor Development

Discussion during the presentation included:

- Sensor description
 - Sensor technology derived from Westinghouse Accident Tolerant Fuel (ATF) in-rod sensor development
 - Wireless sensor located inside dry cask steel canister provides real time data such as temperature and pressure. The sensor does not require penetrations to the canister. Multiple sensors can be interrogated simultaneously.

- Sensor lifetime > 40 years (based on 3.5×10^9 rad estimate for 40-year storage time)
- Long term maximum operating temperature of 425°C
- Sensor application can be used to enable removal of all spent fuel from the pool 1.5 years after shutdown. Wireless sensors permit monitoring of fuel peak cladding temperature during canister loading and transfer to the ISFSI pad.
- Technology overview
 - Pulse induction methods provides simplicity over other powered approaches
 - Minimum number of components
 - Sensor and reference resonant circuits operate at different frequencies
- DOE SNF Canister Sensor Overview
 - In-canister wireless sensor transmits temperature and humidity measurements
 - Sensors located at three axial locations
 - Other sensors and receiver located on canister lid

Questions and comments during the presentation related to sensors included:

- **Question:** Can a measurement from a fuel assembly at the center of a full cask be transmitted to outside of storage systems overpack and/or a transportation overpack? **Response:** Any limit can be overcome by power in transceiver; using a low duty cycle of measurements (maybe 1/day), you can pump power for short time.
- **Question:** How many sensors can be deployed? How reliable are they? **Response:** Need a reference for sensor assembly, and multiple sensors are needed for redundancy. Ten sensors (for example) would need multiple transceivers, since there is a limit to how many sensors can be used on one transceiver.

DOE Transportation Tests

Discussion during the presentation included:

- Video demonstration of multi-modal transportation test with acceleration measurements stored over long time periods.

Questions and comments during the presentation related to sensors included:

- **Comment:** What sensors are needed for transportation will be an important topic - for the community to address in questionnaire.
- **Question:** Are the sensors wireless? **Response:** The sensors were not wireless. The cask lid was modified to get the cables through the lid and into the instrumentation box.

SKB Perspective

Discussion during the presentation included:

- SKB decided to cut in half the amount of decay power permitted in a transport cask. Better information would be valuable to reduce conservatism.


Questions and comments during the presentation related to sensors included:

- **Question:** Knowing the temperatures vs a model could be beneficial; could you put more waste into repository by storing closer? **Response:** The primary parameter of a geological repository is the thermal situation, including the ability to validate temperatures. We already measure temperatures in places.

UK Nuclear AMRC – Challenges of Monitoring Long-term Storage

Discussion during the presentation included:

- Proof of concept project on smart sensors for long-term waste storage
- Among other issues - package is already defined, how do you fit monitoring within existing design.
- Challenges discussion:
 - Wireless vs wired
 - Reliability: 40-year life hasn't been demonstrated
 - Survivability
 - Power supply
 - Data transmission: wired inside canisters and wireless transmission to the outside
 - Attachment: integrated to the canister or attached



Section 3: Canister Sensors Requirements Survey Summary

The final presentation at the December workshop on sensors for spent fuel operations was a review of a survey targeted at eliciting from subject matter experts and stakeholders the desired requirements for sensors in spent fuel storage. This section presents a summary of the survey and a summary of the survey responses.

The survey presented a total of 17 questions, with the questions organized in pages grouped around five topics related to dry storage sensors. The responses to the questions were generally open text fields; survey participants were asked for their response(s) to the question plus an explanation of why the response(s) were selected.

Page 1: Respondent Information

The questions on this survey page were centered on gathering basic information about the survey participants.

Question 1: Contact Information

This section requested basic contact information for each participant. A total of 30 participants provided responses in the survey.

Question 2: Stakeholder Area of Interest

Three different areas of interest were identified in the survey; multiple selections were permitted, so a participant could select one, two, or all three areas of interest. The selections were: 1) Storage Operations, 2) Transportation Operations, and 3) Disposal Operations.

Of the three options, the following areas of interest were indicated:

- Storage Operations: 30/30 responses
- Transportation Operations: 22/30 responses
- Disposal Operations: 17/30 responses

It is noted that these three areas of interest are repeated throughout the survey response. Many of the questions had three text boxes, corresponding to these three areas of interest, permitting respondents to provide input specific to each area of interest as desired.

Page 2: Sensor Attributes

The questions on this survey page were focused on defining the attributes of interest for the sensors.

Question 3: Key Attributes

The text of the question is: “Identify the key attributes to sense (e.g., temperature, relative humidity, helium, oxygen, hydrogen, Kr85 fission gases, thermal gradients, gas concentrations, etc.) and purpose (i.e., operational/regulatory safety/performance objectives) for sensing those attributes.”

A total of 25 responses were provided to this question. Highlights of the responses are as follows:

- **Temperature** was cited as a key attribute in 80% of Storage Operations responses and in 70% of Transportation Operations responses, substantially higher than any other attribute.
- The two most preferred attributes for Disposal Operations were **temperature** (40%) and **humidity** (33%).
- Other key attributes cited for Storage Operations include **thermal gradients** (30%), **humidity** (33%), gas components such as **Kr85**, **oxygen**, and **helium** (20% each), and **canister internal pressure** (20%)
- Other key attributes cited for Transportation Operations include **gas concentrations** (30%) and **acceleration** (25%)
- Other key attributes cited for Disposal Operations include **gas concentrations** (30%) and **external corrosion**.

Question 4: Internal vs External Sensors

The text of the question is: “For the sensor attributes previously identified in Question 3, indicate whether internal and/or external sensors can be used to satisfy the objectives previously identified.”

A total of 24 responses were provided to this question. Highlights of the responses are as follows:

- The responses for this question were split evenly between **internal** and **external** sensors for Storage Operations, Transportation Operations, and Disposal Operations responses. A small number of responses said either would work.

Question 5: Remote vs Wired Internal Sensors

The text of the question is: “Wired internal sensors require through-wall penetrations of casks/canisters. Recent innovations may enable the use of wireless sensing with remote power instead. There are advantages and disadvantages for each method. Indicate the preferred sensing method [remote/wired] and why the method is preferred.”

A total of 24 responses were provided to this question. Highlights of the responses are as follows:

- The preferred method (80% of responses) for Storage Operations, Transportation Operations, and Disposal Operations responses was **remote/wireless** sensors.
- Comments on these responses noted that penetrations for canisters/casks are generally not preferred.

Page 3: Remote Sensors

The questions on this survey page were focused on defining desired performance characteristics for remote sensors.

Question 6: Sensor Lifetime

The text of the question is: “Traditionally, sensors do not survive in extreme environments for extended periods of time. What is the minimum lifetime needed and the aspirational lifetime desired for the sensor attributes previously identified in question 3?”

A total of 21 responses were provided to this question. Highlights of the responses are as follows:

- Responses under Storage Operations were in the range of **3 years to 100 years**, with **10 years** the most common answer (35%).
- Responses under Transport Operations were in the range of **5 years to 20 years**.
- Responses under Disposal Operations were in the range of **5 years to 500 years**, with **10 years** the most common answer (40%).

Question 7: Environmental Qualification

The text of the question is: “Indicate the conditions for which remote sensors need to be qualified (e.g., short-term operations like pressure/temperature differentials and flooded conditions, intense radiation fields, handling/seismic/transportation loads).”

A total of 21 responses were provided to this question. Highlights of the responses are as follows:

- The most preferred response for Storage Operations (70%), Transportation Operations (45%), and Disposal Operations (50%) was **radiation/intense radiation fields**.
- The next most preferred response for all three Operations was **temperature**. Other responses included flooded conditions and seismic loads.

Question 8: Remote Data Collection (Sensing, Transmission, and Receiving Options)

The text of the question is: “Recent innovations in inspection systems have enabled use of robotic delivery systems that can also be used for periodic data collection. For the sensor attributes previously identified, indicate if periodic data collection would satisfy the objectives previously identified in question 3.”

A total of 21 responses were provided to this question. Highlights of the responses are as follows:

- The preferred response (80% of responses) for Storage Operations and Disposal Operations responses was **Yes** periodic collection of data would satisfy the objectives of the sensors.
- The responses for Transportation Operations indicated that neither periodic nor continuous data collection were needed. Instead, collection of data at the beginning and at the end of transportation were indicated as sufficient.

Page 4: Implementation of Sensors

The questions on this survey page were focused on defining the ways in which sensors could be implemented in canisters.

Question 9: Single vs Multiple Sensors

The text of the question is: “For the sensor attributes previously identified in Question 3, indicate if multiple sensors would be desired in order to meet the objectives previously identified.”

A total of 20 responses were provided to this question. Highlights of the responses are as follows:

- **Multiple** sensors were preferred to **single** sensors by a margin of roughly 60% for multiple sensors preferred to 40% for single sensors preferred.
- One respondent noted that **single** sensors can be helpful for event analysis, and multiple strategically placed sensors would be needed for model validation.

- A thread noted among those preferring **single** sensors is that single sensors could be used in multiple casks/canisters to provide information distributed across the installed population. One respondent preferred single sensors while noting that sensors should be considered an information-only enhancement, rather than a safety-significant data source.
- One thread noted among those preferring **multiple** sensors is that multiple sensors would be needed for redundancy (i.e., to protect against sensor malfunction), especially if the sensors would be credited for safety function. Another thread focused on the ability of multiple sensors to provide information about temperature or other attribute gradients within a canister.

Question 10: Sensor Reliability

The text of the question is: “For the sensor attributes previously identified in Question 3, indicate how sensor reliability issues (e.g., potential for false calls, single point of failure, regulatory considerations, etc.) should be addressed.”

A total of 19 responses were provided to this question. Highlights of the responses are as follows:

- Respondents indicated broad support for both highly reliable sensors and for redundant sensors to address concerns of sensor reliability issues.
 - Multiple respondents highlighted a desire for sensors to incorporate a self-monitoring function to indicate defects.
 - Some respondents noted that the reliability requirements could be reduced if multiple sensors are used.
 - One respondent noted the need for a robust modeling and instrumentation methodology to define alarm setpoints for the sensors.
- Respondents indicated that reliability requirements for sensors would be related to the extent to which the sensors form part of the regulatory basis of canister conditions. One respondent noted that if sensors are considered information only, this would reduce the reliability requirements for them.

Question 11: Sensor Reliability over Time

The text of the question is: “For the sensor attributes previously identified in Question 3, indicate the importance for sensor reliability over time for regulatory considerations (e.g., aging management, important to safety function requirements, etc.).”

A total of 20 responses were provided to this question. Highlights of the responses are as follows:

- Respondents noted that the time-sensitive nature of sensor reliability was dependent on a given sensors use case. If the data from a sensor is required during and immediately following drying operations, then there is no requirement for long-duration reliability.
- Some respondents indicated a desired use of sensors to support aging management issues, which would then place high importance on long-duration reliability.

Question 12: Distribution of Sensor(s) and Sampling

The text of the question is: “For the sensor attributes previously identified in Question 3, indicate how sensors should be distributed (i.e., multiple sensors in one cask, one sensor in multiple casks, multiple sensors in multiple casks) in order to meet the objectives previously identified in Question 3.”

A total of 20 responses were provided to this question. Highlights of the responses are as follows:

- More than half of the respondents were in favor of implementing **multiple sensors in multiple casks**. Respondents indicated the influencing factors of redundancy for multiple sensors and broad data availability from multiple casks.
- About 25% of respondents were in favor of **multiple sensors in one cask**, and about 25% of respondents were in favor of **one sensor in multiple casks**.
 - Multiple sensors in one cask was favored among respondents interested in redundancy.
 - One sensor in multiple casks was favored among respondents interested in gathering information.

Question 13: Location of Sensor(s)

The text of the question is: “For the sensor attributes previously identified, indicate the preferred location for that sensor, within the canister/cask, locations external to the canister/cask such as overpack or other. Note that a remote sensor system comprises a sensor and an antenna, and a sensor’s location can be separate from its antenna location.”

A total of 20 responses were provided to this question. Highlights of the responses are as follows:

- About half of the respondents indicated that the sensors should be located **inside** the cask/canister. These respondents were typically interested in temperature and pressure inside the canister, or even in the PWR fuel guide tubes themselves.
- About 25% of respondents were in favor of indicated that the sensors should be located **external to** the cask/canister, and about 25% of respondents indicated the desired location **depended on the desired sensor function**.
 - Suggested locations external to the canister included the external surface of the cask/canister and overpack outlet air vents.
- Respondents also noted the need to align the sensor location with the cask/canister design, striking a balance between the desired sensor information and the canister design requirements.
- A respondent noted that external sensors are replaceable, and therefore reduce the reliability requirements. Malfunctioning external sensors can be replaced much more readily than internal sensors, which are effectively impossible to replace.

Question 14: Effects Considerations

The text of the question is: “Are there potential effects on other safety system functions that need to be considered for sensor applications?”

A total of 17 responses were provided to this question. Highlights of the responses are as follows:

- Respondents noted that the sensor materials must be compatible with the canister metals and local environment. This compatibility should include chemical releases that might occur from the sensor in a high radiation field.
- Respondents noted that sensors should be small enough to avoid impacting flow, including circulating flow inside the canister (for internal sensors) and convective flow inside the overpack (for external sensors).
- A Failure Modes and Effects Analysis (FMEA) was recommended as the process to use in testing potential sensors and their implementation for adverse effects on the cask/canister environment.

Page 5: Additional Considerations

The questions on this survey page were focused on additional topics related to sensors used in canister storage.

Question 15: Potential Benefits of Sensors

The text of the question is: “What benefits (e.g., streamlined licensing and aging management, improved public confidence in continued spent fuel storage, etc.) may be needed in order to justify the costs of sensor implementation?”

A total of 20 responses were provided to this question. Highlights of the responses are as follows:

- Several respondents identified **improved public confidence** as a potential benefit. One respondent noted that members of the public have repeatedly expressed concern about the safety and confinement integrity of cask/canister spent fuel storage. However, another respondent cautioned against relying on sensors for public outreach, due to likely limitations in the total duration of reliable sensors.
- Other respondents identified **streamlined licensing** as a potential benefit. The ability to run with tighter margin to limits resulting from more data being available on the storage system was envisioned as a means of cost benefit from streamlined licensing.
- Use of sensors for **aging management** was also cited by respondents as a potential benefit, with increased confidence in system internal and external conditions potentially leading to reducing inspection burden.
- For Disposal Operations, respondents noted that having information about the performance of the cask/canister prior to fuel receipt would be valuable in determining the acceptance criteria and disposition method for an interim or final repository. One example provided is if re-packaging was not required because of information provided by sensors, that would provide significant benefits and cost justification.

Question 16: Potential Risks of Sensor Implementation

The text of the question is: “What are the risks associated with sensor implementation (e.g., false calls, data reliability, regulatory oversight, public scrutiny)?”

A total of 20 responses were provided to this question. Highlights of the responses are as follows:

- Several respondents identified **false calls/data reliability** as a potential risk for sensor implementation. Respondents identified as a concern a false call that would lead to additional inspection or remediation activities for the canister or even repackaging the fuel; this type of an event would negate any potential cost benefits associated with sensors due to operations cost and occupational dose. Also raised was the concern that a false call would lead to additional public or regulatory scrutiny.
- The potential for false calls was also used to highlight the need for confirmatory actions (like multiple sensors), particularly for sensors that are difficult to verify or replace.

- Another potential risk identified is if the use of sensors, or the data provided by the sensors, leads to additional regulatory requirements on cask/canister storage.
- The risks associated with sensor implementation may influence the types of sensors desired for pursuit. One respondent noted that external corrosion sensors would be easier to verify and replace if needed.

Question 17: Other Applications

The text of the question is: “Are there additional possible applications of remote sensors for nuclear wastes (e.g., nonproliferation, other fuel forms, etc.)?”

A total of 17 responses were provided to this question. Highlights of the responses are as follows:

- Many of the responses provided were limited on specific applications, but expressed confidence that additional uses would be found for sensors in high radiation environments.
- Specific examples of other applications cited by respondents included:
 - Nuclear waste repositories/waste disposition
 - Tracking of parts during decommissioning of power plants
 - Non-proliferation, to verify that all nuclear materials have not been moved or disturbed
 - Space sector



Section 4: Conclusions

The use of sensors in spent fuel storage applications has been identified as a way to enable opportunities for a more balanced approach to spent fuel. By reducing certain margins while ensuring the public health and safety is maintained and reducing worker dose, an overall increase in safety can be achieved.

An initial step in defining the desired performance characteristics for the types of sensors that might be used for spent fuel storage included a two-day workshop on sensors for spent fuel operations. The presenters and the attendees were stakeholders from various areas of spent fuel management, including storage, transportation, and disposal. The workshop was used to introduce a survey designed to elicit stakeholder input related to sensor attributes and performance characteristics. This report summarizes the results of the workshop and the survey.

Key conclusions from the workshop and survey on the performance objectives for use of sensors in spent fuel applications are as follows.

- While there were no ideas or concepts raised that resulted in uniform support, a handful of concepts were strongly supported by most survey respondents:
 - The temperature of the cask/canister internal environment is an attribute of interest for use in casks/canisters under Storage Operations, Transport Operations, and Disposal Operations
 - If sensors are to be used that are internal to the cask/canister, the method of data transmission should be a wireless remote method. Penetrations through the cask/canister to permit wired sensors, such as the thermocouple lances used for the HBU Demo cask, were strongly disfavored by the stakeholder responses.
- The stakeholders offered differing opinions on the potential for implementation of sensors for licensing or regulatory benefit. Some stakeholders expressed the view that sensors are best used as informational purposes only. However, other stakeholders noted that the cost of implementing sensors would generally be expected to be offset by reductions in regulatory and licensing burden. For this to occur, sensors would need to take on a safety-related role for loading and short-term storage operations. This may be accomplished by progressing from the current regulatory approach using conservative design licensing basis models to one based on regulatory compliance demonstration to actual sensor data confirmation

during loading and short-term operations. This alternate data based licensing approach would be optional to the current traditional models-based approach.

- Stakeholders from operating plants firmly expressed the view that sensors should be an optional technology, and not implemented as a requirement.
- Many stakeholders noted that the reliability requirements of sensors increase substantially if the sensors will be used for licensing or regulatory benefit. In order to achieve sufficient reliability, it may be necessary to use multiple sensors in a cask/canister.



Appendix A: Translated Table of Contents

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THE ELECTRIC POWER RESEARCH INSTITUTE (EPRI) PREPARED THIS REPORT.

乏燃料作業中遙感器的 性能要求

利益相關方對乾燥直筒式儲存、運輸
和處置的建議概要

本產品適用EPRI（電力科學研究院）核子質量保證的
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YES



摘要

EPRI 正在與美國能源部（DOE）、美國核電管理委員會（NRC）、核能研究所（NEI）以及國內和國際核設施、各國家實驗室、乾式儲存供應商和研究與開發組織合作，以期提高乾燥儲存系統內部環境相關知識。本工作中確定的一種方法是在極端放射性環境地點使用傳感器測量諸如峰值夾層溫度等環境參數的潛在機會。如果成功，這些傳感器可用於多種潛在應用，在極端環境中（如高放廢物罐、深層地質儲存庫等）直接測量可能有用的情況。

本報告概述了為支持制定高放射性環境所用傳感器的預期性能要求而採取的行動，重點是乏燃料生命周期的不同方面（即儲存、運輸和處置）。EPRI 主辦組織了一次研討會，與會人員包括美國能源部、核管制委員會、各國家實驗室、國內和國際核設施、乾燥存儲供應商和其他研發組織的多位主題專家，涉及後端運營所需傳感器的性能要求。此外，還面向主題專家編製了一份所需傳感器屬性和性能相關調查問卷，收集答覆並匯總入本報告。

關鍵字
乏燃料
傳感器

目錄

摘要	V
執行摘要..	VII
第 1 節： 簡介	1-1
背景.....	1-1
方法.....	1-2
第 2 節： 直筒研討會概要.....	2-1
研討會議程.....	2-1
發言和討論摘要	2-1
高燃耗示範罐熱電偶.....	2-2
用於 HBU 演示的傳感器選項和經驗教訓.....	2-3
傳感器行業展望.....	2-3
X 波創新直筒內部傳感器	2-4
原子能機構對傳感器的展望.....	2-5
西屋傳感器開發.....	2-6
DOE 運輸試驗	2-7
SKB 展望	2-8
英國核 AMRC-監測長期儲存的挑戰.....	2-8
第 3 節： 直筒傳感器需求調查問卷概要	3-1
第 1 頁:答復人資料	3-1
問題 1:聯絡資料	3-1
問題 2:利益相關方感興趣領域	3-1
第 2 頁:傳感器屬性	3-2
問題 3:關鍵屬性	3-2
問題 4:內部與外部傳感器.....	3-2
問題 5:遠程與有線內部傳感器	3-3
第 3 頁:遙感器.....	3-3
問題 6:傳感器壽命	3-3
問題 7:環境資質	3-3

問題 8:遠程數據收集 (感知、傳輸和接收選項)	3-4
第 4 頁:傳感器部署	3-4
問題 9:單傳感器與多傳感器.....	3-4
問題 10:傳感器可靠性	3-5
問題 11:傳感器可靠性隨時間變化情況.....	3-5
問題 12:傳感器分佈與採樣	3-6
問題 13:傳感器位置	3-6
問題 14:影響因素	3-7
第 4 頁:其他注意事項	3-7
問題 15:傳感器潛在益處.....	3-8
問題 16:傳感器部署的潛在風險.....	3-8
問題 17:其他應用	3-9
第 4 節: 結論	4-1

使用済み燃料の作業に おける遠隔センサーの 性能要件

乾式キャニスターの貯蔵、輸送、お
よび廃棄に関する利害関係者からの
意見のまとめ

本成果物には、EPRI 原子力品質保証プログラム
(Nuclear Quality Assurance Program)
の要件の全てまたは一部が適用される。

YES



要約

EPRI は、米国エネルギー省 (DOE)、米国原子力規制委員会 (NRC)、原子力エネルギー協会 (NEI)、および国内外の事業者、国立研究所、乾式貯蔵施設関連ベンダー、研究開発機関と協力し、乾式貯蔵システムの内部環境に関する知見の向上に取り組んでいる。本研究では、極度の放射能環境下にある場所で、被覆管のピーク温度などの、環境パラメータを測定するためにセンサーの使用を可能にする潜在的な機会が、アプローチの一つとして特定された。成功すれば、これらのセンサーは、高レベル廃棄物タンクや深地層処分場など、極限環境での直接測定が有効な、さまざまな潜在的用途に使える可能性がある。

本報告書は、使用済み燃料のライフサイクル（すなわち貯蔵、輸送、および廃棄）のさまざまな側面に焦点を当て、高放射能環境で使用されるセンサーに求められる性能要件の開発を支援するために実施された活動を要約したものである。EPRI は、DOE、NRC、国立研究所、国内外の事業者、乾式貯蔵施設関連ベンダー、その他の研究開発組織から分野別専門家を集め、バックエンド作業に向けたセンサーに求められる性能要件に関するワークショップの主催と進行を務めた。さらに、分野別専門家向けに、必要なセンサーの属性および性能に関するアンケートが作成され、収集された回答が本報告書にまとめられている。

キーワード
使用済み燃料
センサー

目次

要約	V
エグゼクティブサマリー	VII
セクション 1 :	はじめに
.....	1-1
背景	1-1
アプローチ	1-2
セクション 2 : ... キャニスターワークショップのまとめ	2-1
ワークショップのアジェンダ	2-1
プレゼンテーションと議論のまとめ	2-1
高燃焼度実証試験用キャスク熱電対	2-2
HBU 実証試験に向けたセンサーオプションと教訓	2-3
センサーの業界的展望	2-3
X-Wave Innovations キャニスター内部センサー	2-4
センサーに関する IAEA の展望	2-5
Westinghouse のセンサー開発	2-6
DOE 輸送試験	2-7
SKB の展望	2-8
英国 NAMRC - 長期貯蔵施設監視の課題	2-8
セクション 3 : . キャニスターセンサーの要件調査のまとめ	3-1
ページ 1 : 回答者に関する情報	3-1
質問 1 : 連絡先情報	3-1
質問 2 : 利害関係者にとって関心のある分野	3-1
ページ 2 : センサーの属性	3-2

質問 3 : 主な属性	3-2
質問 4 : 内部センサー 対 外部センサー	3-2
質問 5 : 遠隔センサー 対 有線内部センサー	3-3
ページ 3 : 遠隔センサー	3-3
質問 6 : センサーの寿命	3-3
質問 7 : 環境認定	3-3
質問 8 : 遠隔データ収集 (検出、送信、受信のオプション)	3-4
ページ 4 : センサーの実装	3-4
質問 9 : 単一センサー 対 多重センサー	3-4
質問 10 : センサーの信頼性	3-5
質問 11 : センサーの経時的な信頼性	3-5
質問 12 : センサーの配置とサンプリング	3-6
質問 13 : センサーの場所	3-6
質問 14 : 影響に関する考慮事項	3-7
ページ 5 : 追加の考慮事項	3-7
質問 15 : センサーの潜在的な利点	3-8
質問 16 : センサーを実装することによる潜在的なリスク	3-8
質問 17 : 他用途への適用	3-9
セクション 4 :	結論
.....	4-1

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사용후 핵연료
센서

목차

초록	V
개요	VII
섹션 1: 소개	1-1
배경	1-1
접근법	1-2
섹션 2: 캐니스터 워크숍 요약.....	2-1
워크숍 의제	2-1
발표 및 토의 요약	2-1
고연소도 시연 연료수송용기 열전대	2-2
HBU 시연용 센서 옵션 및 교훈	2-3
센서에 대한 업계 시각	2-3
X-파 혁신 캐니스터 내부 센서	2-4
센서에 대한 IAEA 시각	2-5
Westinghouse 센서 개발	2-6
DOE 운송 시험	2-7
SKB 시각	2-8
영국원자력 AMRC - 장기 저장 모니터링의 문제	2-8
섹션 3: 캐니스터 센서 요구사항 조사 요약.....	3-1
1 페이지:응답자 정보	3-1
질의 1:연락처	3-1
질의 2:이해관계자 관심 영역	3-1
2 페이지:센서 속성	3-2
질의 3:핵심 속성	3-2
질의 4:내부 센서 대 외부 센서	3-2
질의 5:원격 센서 대 내부 유선 센서	3-3
3 페이지:원격 센서	3-3
질의 6:센서 수명	3-3
질의 7:내환경검증 (EQ)	3-3

질의 8:원격 데이터 수집(감지, 전송 및 수신 옵션).....	3-4
4 페이지:센서 적용.....	3-4
질의 9:단일 센서 대 다중 센서.....	3-4
질의 10:센서 신뢰성	3-5
질의 10:시간에 따른 센서 신뢰성.....	3-5
질의 12:센서 분산 및 샘플링	3-6
질의 13:센서 위치.....	3-6
질의 14:영향 고려사항	3-7
5 페이지:추가 고려사항.....	3-7
질의 15:센서의 잠재적 이익	3-8
질의 16:센서 적용의 잠재적 위험.....	3-8
질의 17:기타 적용.....	3-9
섹션 4: 결론	4-1

Requisitos de funcionamiento de los sensores remotos en operaciones con combustible gastado

Resumen de la información suministrada por las partes interesadas sobre la eliminación, el transporte y el almacenamiento en seco en cápsulas

Este producto está sujeto a la totalidad o a parte de los requisitos del Programa de garantía de calidad nuclear de EPRI.

YES





Resumen

EPRI colabora con el Departamento de Energía (DOE) de EE. UU., la Comisión Reguladora de la Energía Nuclear (NRC) de EE. UU., el Instituto de Energía Nuclear (NEI) y las empresas de servicios nacionales e internacionales, laboratorios nacionales, proveedores de almacenamiento en seco, así como con organizaciones de investigación y desarrollo para mejorar los conocimientos relativos al entorno interno de los sistemas de almacenamiento en seco. En este trabajo, se ha identificado una posible oportunidad de permitir el uso de sensores en aquellas ubicaciones con entornos radiactivos extremos para medir los parámetros del entorno, como la temperatura máxima de las vainas. Si fuera posible, estos sensores podrían usarse en varias aplicaciones donde las mediciones directas podrían ser útiles en entornos extremos, como los tanques de residuos de alta actividad, los almacenamientos geológicos profundos, etc.

Este informe resume las actividades realizadas para apoyar el desarrollo de los requisitos de funcionamiento que podrían esperarse de los sensores usados en entornos altamente radiactivos, con especial interés en los distintos aspectos del ciclo de vida del combustible gastado (como el almacenamiento, el transporte y la eliminación). EPRI organizó y facilitó un taller de trabajo con expertos en la materia del DOE, la NRC, laboratorios nacionales, empresas de servicios nacionales e internacionales, proveedores de almacenamiento en seco y otras organizaciones de investigación y desarrollo, dedicado a los requisitos de funcionamiento que se esperan de los sensores durante las operaciones de la parte final del ciclo. Asimismo, para los expertos en la materia, se elaboró un cuestionario sobre las características y el funcionamiento deseados de los sensores y, en este informe, se han recopilado y resumido las respuestas.

Palabras clave

Combustible gastado

Sensores

Resumen.....	V
Resumen ejecutivo	VII
Sección 1: Introducción.....	1-1
Antecedentes.....	1-1
Planteamiento.....	1-2
Sección 2: Resumen del taller de trabajo sobre las cápsulas	2-1
Programación del taller de trabajo	2-1
Resumen de las presentaciones y el debate	2-1
Termopares del contenedor de demostración de alto quemado	2-2
Opciones de sensores y enseñanzas extraídas de la demostración de alto quemado.....	2-3
Perspectivas del sector sobre los sensores.....	2-3
Sensores internos con innovaciones de ondas X en las cápsulas.....	2-4
Perspectivas sobre los sensores del Organismo Internacional de Energía Atómica (IAEA).....	2-5
Desarrollo de sensores de Westinghouse.....	2-6
Ensayos de transporte del DOE.....	2-7
Perspectivas de SKB	2-8
Centro de Investigación en Fabricación Avanzada (AMRC) del Reino Unido: retos de la monitorización del almacenamiento a largo plazo	2-8
Sección 3: Resumen de la encuesta sobre requisitos de los sensores de las cápsulas	3-1
Página 1: Información sobre las personas encuestadas	3-1
Pregunta 1: Información de contacto.....	3-1
Pregunta 2: Área de interés de las partes interesadas	3-1
Página 2: Características de los sensores.....	3-2
Pregunta 3: Principales características.....	3-2
Pregunta 4: Sensores externos frente a sensores internos	3-2

Pregunta 5: Sensores internos inalámbricos frente a cableados.....	3-3
Página 3: Sensores inalámbricos.....	3-3
Pregunta 6: Vida útil de los sensores.....	3-3
Pregunta 7: Calificación medioambiental.....	3-3
Pregunta 8: Recopilación de datos de forma remota (opciones de detección, transmisión y recepción)	3-4
Página 4: Implementación de los sensores.....	3-4
Pregunta 9: Uso de un sensor frente a varios sensores.....	3-4
Pregunta 10: Fiabilidad de los sensores.....	3-5
Pregunta 11: Fiabilidad de los sensores a lo largo del tiempo	3-5
Pregunta 12: Distribución de los sensores y muestreo	3-6
Pregunta 13: Ubicación de los sensores.....	3-6
Pregunta 14: Consideraciones sobre los efectos	3-7
Página 5: Consideraciones adicionales.....	3-7
Pregunta 15: Posibles beneficios de los sensores	3-8
Pregunta 16: Riesgos potenciales de la implementación de los sensores	3-8
Pregunta 17: Otras aplicaciones.....	3-9

Sección 4: Conclusiones4-1



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