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subject: **Uncertainty quantification methodologies development for storage and transportation of used nuclear fuel: Pilot study on stress corrosion cracking of canister welds**

This letter report documents the technical basis and results from the pilot study for the development of uncertainty quantification (UQ) methodologies to quantify and characterize the uncertainty associated with the degradation mechanisms impacting normal dry storage operations for used nuclear fuel (UNF) and normal conditions of transport in support of the Used Fuel Disposition (UFD) Campaign and its effectiveness to rank the data needs and parameters of interest. As an illustration of the methodology, this report assesses whether uncertainties in the probabilistic model for atmospheric stress corrosion cracking (SCC) of welded canisters and the associated thermal profiles can be reduced sufficiently to make such models valuable.

Scope: The near-term objectives of the UFD Campaign's Storage and Transportation (S&T) task within the US Department of Energy's Office of Nuclear Energy (DOE-NE) are to use a science-based approach to develop the technical bases to support the continued safe and secure storage of UNF, develop technical bases for retrieval of UNF after extended storage,

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and develop the technical bases for the transport of high burnup fuel after extended periods of dry storage. Prior efforts by UFD and other organizations (e.g., Nuclear Regulatory Commission [NRC], Nuclear Waste Technical Review Board [NWTRB]) and other countries (including Hungary, Korea, Japan, Germany, Spain and the United Kingdom [UK]) have identified and ranked data needs and modeling needs (also termed "gaps") to complete the technical bases for extended storage. Technical needs were ranked on both their likelihood and the consequence (impact) on licensability and thus safety. Given the large scope, and the large number of high and medium priority data and modeling needs identified for the development of the desired technical bases for the extended storage and transportation of UNF, uncertainty quantification (UQ) tools and methodologies are required to provide an informed guidance on the most influential/critical research with the highest payoff (in this case, exemplified by a significantly greater understanding to improve initial or renewal licensing).

UQ methodology process for application to UFDC R&D objectives: The overall UQ methodology for its application to degradation mechanisms identified within the UFDC is divided into five tasks:

1. Identify performance characteristics for specific degradation mechanisms (atmospheric stress corrosion cracking of welded canisters in this pilot study).
2. Link the degradation mechanisms to the regulatory requirements in a mathematical framework: understand performance requirements in a mathematical formulation.
3. Analyze the composition of available data (experimental and numerical): identifying the uncertainties associated with the degradation mechanisms (in this case atmospheric SCC) and associated cross-cutting needs (in this case thermal profile).
4. Perform preliminary decision making analysis.
5. Identify performance characteristics with insufficient data: rank phenomena/input parameters based on performance requirements.

Tasks 1–3 address the objective of *developing a methodology to quantify and characterize the uncertainty associated with the degradation mechanisms.* Tasks 4 and 5 deal with the second objective of *demonstrating the effectiveness of this approach to rank the data needs and parameters of interest.* This conceptual UQ methodology supporting analysis of storage and transport of used nuclear fuel provides:

- A way to formally describe that analysis and then,
- A clear path from formal description to computational implementation to written documentation.

Illustration of the methodology to atmospheric SCC: The application of UQ in this pilot study has been demonstrated on a specific degradation mechanism, namely, environmentally (chloride-) induced stress corrosion cracking (SCC) of welded canisters. This example represents gaps in knowledge, data and models for a phenomenon ranked "very high" for both likelihood and consequence. Although the state of knowledge regarding atmospheric corrosion in general is mature enough to identify the conditions necessary for corrosion (environment, residual stress and material susceptibility), it is not clear if these conditions exist now (or in the future) at specific storage locations. The thermal profile cross-cutting need, whose closure is necessary to provide inputs to SCC analyses was selected to illustrate the necessity of incorporating cross-cutting needs to understand the uncertainty in the inputs they provide to the model. The remaining cross-cutting needs are not considered in this pilot study.

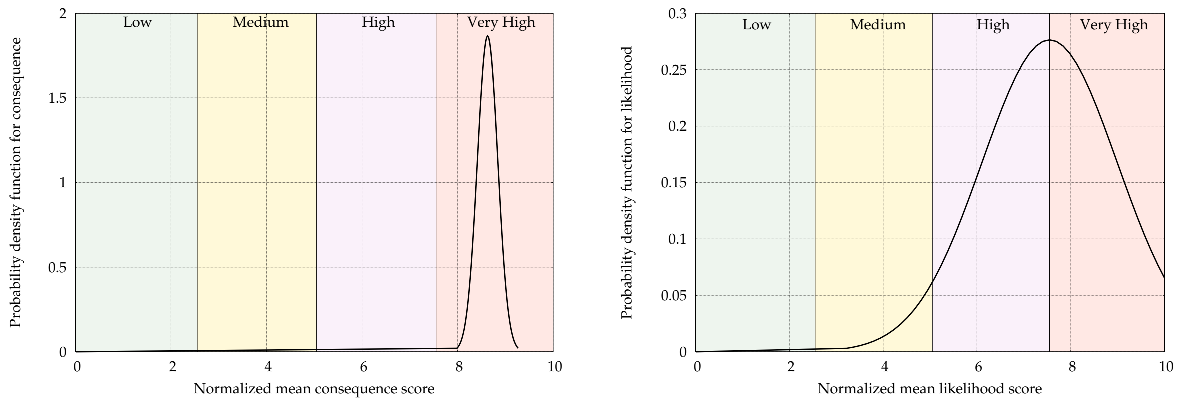
Identification of performance requirements applicable to atmospheric stress corrosion cracking of welded canisters (Task 1): The regulatory requirements for site-specific and general licenses for storage and transportation of used nuclear fuel (UNF) pertaining to atmospheric SCC are described in Title 10 of the Code of Federal Regulations (10 CFR) Part 72 "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater than Class C Waste" (10CFR 72.3, 10CFR 72.166, 10CFR 72.236). Additional regulatory guidance can be found and extracted from a series of Spent Fuel Storage and Transportation Interim Staff Guidance, NUREG, NUREG/CRs, and industry standards documents (NUREG-1536, ANSI N14.5-1997). In the context of the pilot study, this work focuses on the confinement function.

The above mentioned regulatory requirements (regulatory verbiage) were converted into the quantifiable performance of no through-wall SCC penetration. This metric permits meaningful uncertainty and sensitivity analyses of the atmospheric SCC model.

Link atmospheric stress corrosion cracking to the regulatory requirements in a mathematical framework (Task 2): The US and other countries gap reviews identified the atmospheric corrosion of welded canisters degradation mechanism as high on their scales. As summarized in Fig. 1(a) and (b) this task has extracted and summarized the consequence and likelihood levels for atmospheric stress corrosion cracking from these gap reviews and created normalized distribution probability density functions for the mean normalized consequence and likelihood scores (see Fig. 1(a)). Definition of such probabilities distribution corresponds to a probability space for the likelihood and consequence uncertainty and provide the answers to the questions "*How likely is it to happen?*" and "*What are the consequences if it happens?*".

Development of a numerical model for atmospheric SCC with inclusion of uncertainty (Task 3): This step corresponds to the selection, development and running of numerical model representing the degradation mechanism of interest, in this case atmospheric SCC.

A prototype SCC model for welded canisters similar to those stored in marine environments was constructed leveraging existing corrosion models and the GoldSim commercial software framework. The pilot study problem includes relevant physical phenomena that collectively describe SCC of welded canisters in marine environments. The analytical output of the pilot study is a probabilistic evaluation of the likelihood (and time in storage) of welded canisters to develop through-wall cracks for a storage system and thermal load similar to systems



(a) Consequence level **(b)** Likelihood level

Figure 1. Normal distribution probability density function for normalized (a) consequence and (b) likelihood scores.

currently housed at the representative storage facility, subsequently identifying areas for more focused attention, allowing primary degradation mechanisms to be compared quantitatively.

The SCC model evaluates the environmental conditions on the surface of the storage canister as a function of surface location and time, and determines when the environmental conditions at a given location support localized corrosion. Pit initiation and growth lead to SCC crack initiation and growth which are tracked at selected locations until a crack forms or 100 years of storage have occurred.

Probability distribution functions describing the various parameters characterizing relevant physical phenomena and corrosive conditions that collectively describe SCC of welded canisters have been extracted from literature data review including both field data, laboratory test data and numerical analyses. Ambient temperature, relative humidity, pit growth rate, crack growth rate, weld residual stresses and weld location are the physical and geometrical parameters that were considered uncertain.

Probability of the time in storage before the first through-wall crack occurs: Storage duration before the onset of the first through-wall crack is the output selected to estimate the metric related to SCC of welded canisters. A short duration (e.g. within 10 years) considered a high consequence, and a long duration (e.g. more than 40 years) is considered a moderate consequence. In order to quantify and rank the importance of the variance of each uncertain input on the variance of the output of interest (probability of through-wall crack occurring during storage), sensitivities analyses were conducted.

Using a probabilistic model, one base case and three sensitivity analyses were conducted for this pilot study in which the uncertainty in storage time before the first through-wall crack occurs is estimated via a sampling-based method. The reference case examined a 24 kW heat load, a 15% relative humidity threshold and a randomly estimated stress field through the thickness of the weld.

The current regulatory framework supports at least the first 80 years of dry cask storage (including the initial licensing and maximum renewal). It is important to note that 10 CFR 72 does not define confinement as complete isolation, rather defines site dose limits, so through-wall cracks do not necessarily mean failure to meet the regulations. However, the crack growth (and the size of the crack) are factors in the leak rate and subsequent calculation of dose.

The input parameters having the biggest impact on the time in storage before the first through wall crack occurs were identified as being (i) crack growth rate at 80°C, (ii) crack growth rate pre-factor at fixed reference conditions, (iii) location of the second weld (with respect to the center line of the canister), and (iv) crack growth exponent; with the top two input parameters leading to 60-80% of the variance, while the location of the second weld. These are areas identified for additional research to improve uncertainty.

An evaluation of the through-wall crack sensitivity to heat load, limiting relative humidity and weld residual stress was also performed. The speed at which a pit/crack initiates and propagates through the canister wall thickness depends on the temperature of the canister, so heat load was evaluated for 10 kW and 4 kW heat loads in addition to the reference case (24 kW) and a 10 kW case with a 12-year offset representing the absence of corrosive dust deposition before storage. The relative humidity threshold controls the conditions at which SCC can occur and uncertainty exists in the actual limiting RH, so analyses were performed at 15% and 20% RH. An alternative weld residual stress approach was used with a constant weld residual stress profile (in the absence of modeling capabilities and material properties that capture the complexity of a profile as outlined by NRC). The results highlight the need to better understand (reduce uncertainty in) thermal profile, limiting-RH leading to corrosion of canister materials, and material properties/weld residual stress. The results also show that credit could be taken for the time period that canisters are not exposed to chloride containing aerosols before placement at storage facilities.

Recommendations: The recommendations for future development of uncertainty quantification methodologies to provide guidance on which data, once obtained, will have the greatest impact on meeting the UFD ST R&D objectives include:

- Comparison of multiple degradation mechanisms and identification of performance characteristics with insufficient data
  - Perform uncertainty quantification analysis to quantify and characterize the uncertainty associated with several selected degradation mechanisms impacting normal dry storage operations and normal conditions of transport.
  - Degradation mechanisms to consider include: atmospheric stress corrosion cracking (SSC: welded canisters, ranked 2 in UFDC gap prioritization report), hydride reorientation and delayed hydride cracking (SSC: cladding, ranked 4).
  - Cross cutting need considered include: thermal profiles (ranked 1), stress profile (ranked 1) and drying issues (ranked 3).

  - Ranking the degradation mechanisms and quantifying how much the data uncertainty affects this ranking.
  - Ranking the joint input space common to all degradation mechanisms
  - Ranking disjoint input spaces specific to each degradation mechanisms.

- Improvement of uncertainty characterization and sampling strategies:
  - Inclusion of the appropriate separation of aleatory and epistemic uncertainty.
  - Importance sampling or other reliability methods need to be considered.

- Improvement of the atmospheric chloride induced stress corrosion cracking model of welded used fuel storage canisters in marine locations:
  - Inclusion of pre-existing manufacturing defects should be considered.
  - Improvement of the functional form representing the weld residual profile through the thickness of the canister wall.
  - Modification of the pit initiation and pit growth model and their dependence on the aqueous environment.
  - Inclusion of chloride dependence of the crack growth rate equation.
  - Integration of alternative conceptual model such as intergranular SCC of sensitized stainless steel using a model based on percolation theory.
  - Integration of a crack coalescence model.
  - Expansion of material properties beyond 304 stainless steel.

The classification of uncertainty is very important to understanding the uncertainty in the probability associated with the performance metric chosen. Uncertainty is not trivial and needs involvement at all levels of development of a complex system. Knowing which variables control the performance metric and what part of the uncertainty in those variables is epistemic and can be reduced will not only inform the UFDC decision makers, but will also help direct future research in this area.

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