WHY RISK ASSESSMENT IN LONG-TERM STORAGE OF SPENT NUCLEAR FUEL?

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Abstract

This paper presents probabilistic risk-informed approaches that the Nuclear Regulatory Commission (NRC) staff is planning to consider in preparing regulatory bases for long-term storage of spent nuclear fuel (SNF) for up to 300 years. Due to uncertainties associated with long-term SNF storage, the NRC is considering a probabilistic risk-informed approach as well as a deterministic design-based approach. The uncertainties considered here are primarily associated with materials aging of the canister and SNF in the cask system during long-term storage of SNF. This paper discusses some potential risk contributors involved in long-term SNF storage. Methods of performance evaluation are presented that assess the various types of risks involved. They include deterministic evaluation, probabilistic evaluation, and consequence assessment under normal conditions and the conditions of accidents and natural hazards. Some potentially important technical issues resulting from the consideration of a probabilistic risk-informed evaluation of the cask system performance are discussed for the canister and SNF integrity. These issues are also discussed in comparison with the deterministic approach for comparison purposes, as appropriate. Probabilistic risk-informed methods can provide insights that deterministic methods may not capture. Two specific examples include stress corrosion cracking of the canister and hydrogen-induced cladding failure. These examples are discussed in more detail, in terms of their effects on radionuclide release and nuclear subcriticality associated with the failure. The plan to consider the probabilistic risk-informed approaches is anticipated to provide helpful regulatory insights for long-term storage of SNF that provide reasonable assurance for public health and safety.

1. Introduction

Applying both a probabilistic risk-informed approach and deterministic approach helps the staff confirm the adequacy of existing regulatory bases or augment the regulatory bases to cover long-term storage of SNF. Such reviews are performed to provide reasonable assurance for public health and safety. This paper presents some probabilistic risk-informed and deterministic approaches that the NRC staff is planning to investigate in its review of long-term storage of SNF for up to 300 years. Due to uncertainties associated with long-term SNF storage, the NRC staff is considering both the probabilistic risk-informed and deterministic design-based approaches. The uncertainties considered here are primarily associated with materials aging. This paper discusses some potential technical issues associated with materials aging for the cask system. The cask system that stores SNF consists of components, such as the canister, SNF and overpacks.

Deterministic safety assessment methods that apply conservative assumptions may not provide performance insights that a probabilistic risk-informed performance based method may identify. A conservative deterministic method may not fully address insights that uncertainties may have during long-term materials aging for each failure mode. A probabilistic risk-informed approach allows the safety assessment of the cask system to be performed using realistic assumptions that incorporate uncertainty analyses and thereby assess the system's performance under a variety of conditions.

This paper considers some performance criteria in the probabilistic risk-informed approach under normal, accident, or natural hazard conditions. Methods of performance evaluation are also considered. And, some potentially important technical issues associated with long-term materials aging in the canister and SNF are discussed for the canister and SNF integrity. These issues are also discussed when comparing the deterministic approach, as appropriate. Two example issues, marine stress corrosion cracking (SCC) of the stainless steel canister and hydrogen embrittlement of Zircaloy cladding are discussed in more detail, in terms of their potential effects on radionuclide release and nuclear subcriticality, as risk-informed performance measures.

2. Potentially important technical issues associated with long-term materials aging

In the probabilistic risk-informed approach, three questions on risk are asked: (i) what can go wrong? (ii) How likely is it? and (iii) What are the consequences? Accounting for uncertainties associated with long-term materials aging to the canister and SNF, the NRC staff's technical approach will, for example, consider the following:

- Preventing nuclear criticality, due to degradation of SNF, the canister , or neutron absorbers
- Preventing unacceptable release of radioactive material (i.e., confinement), due to degradation of the seal, the canister, and SNF
- Avoiding excessive radiation dose rates and doses (i.e., radiation shielding), due to degradation of shielding material
- Maintaining the retrievability of the contents under SNF degradation.
- Physical protection and security
- Maintenance programs

During its evaluation, the staff will assess the following:

- SNF specifications – not limited to type of SNF, uranium mass loading, cladding material, specification of damaged SNF, enrichment, heat load as a function of cooling time and heat dissipation, source term, dimensions, burnups and loading curves, inerting atmosphere, maximum storage time, and operating history.
- Structural capability of the cask system to withstand loads under accident conditions and natural phenomena events
- Heat removal under normal, loading, off-normal, and accident conditions
- Maintaining confinement
- Compliance with regulatory dose limits in air and direct radiation from the cask system
- Maintaining nuclear subcritical condition

3. Methods of performance evaluation of cask system

The staff is planning to consider the following methods of performance evaluation of the cask system.

Deterministic modeling techniques which have been widely used to support design-based regulatory requirements. Examples include laboratory test results and rigorous numerical modeling in the structural, thermal and criticality assessment. A deterministic modeling technique typically consists of bounding analyses that obtain their basis from engineering and scientific methods and experimental test results that are expected to bound the potential accident conditions. Consensus standards or regulatory guides provide examples of acceptable approaches to meeting deterministic regulatory requirements.

The probabilistic modeling technique is an extension of deterministic methods. It is based on extended event identification and the associated failure mechanisms, the probability and probability cut-off of the failure mechanisms, the uncertainties and variability, and incorporation of the system consequence analysis. The probabilistic modeling of the overall cask system is consistent with the risk-informed approach. This enables optimizing inspection programs and identifying mitigation techniques for the design and operation of the cask system. The probabilistic modeling of the overall cask system will also help in early identification of potentially risk-significant issues. Example computer codes that may be applicable to the risk assessment of the cask system include SAPHIRE [1], MELCOR [2], MACCS2 [3], RSAC [4], and PCSA [5]. Applications of these codes to cask systems are available in NRC [6] and EPRI [7] reports. The probabilistic modeling of the overall cask system can be fixed in time or modeled as time-dependent.

The probability of external initiating events or event sequences affecting the cask performance after long-term storage are assessed under normal, various accident and natural hazard conditions. Examples of the external initiating events include aircraft hazards and seismic events. Examples of event sequences include cask tip-over, weld failure, heatup, or SNF failure. Maintaining subcritical SNF conditions is assessed. The assessment of nuclear subcriticality may include (i) moderator exclusion, (ii) configuration stability of the SNF assemblies and internal structures, (iii) effectiveness of neutron absorber, and (iv) burnup credit. The consequence considered is dose (or cancer fatality) to the worker or to the public from radionuclide release.

4. Consideration of potential technical issues in canister and SNF

Failure mode and effect analyses are integral to safety assessments. For the list below, some potentially important factors in the probabilistic risk-informed approach are emphasized for each failure mode.

- Mechanical failure of the stainless steel canister – Canister breach from mechanical puncture resulting from excessive impact stresses. A cut-off probability is used to exclude breach at welds as a function of impact stress [6]. The breached area will affect the magnitude of the radionuclide release fraction. Depending on the magnitude, the impact failure may lead to a configurational change in internal structure that affects the nuclear subcriticality assessment, and the retrievability of the SNF materials.

- SCC of stainless steel canister – In a marine (coastal) environment with salt deposits on the canister from salt water droplets in the air, the weld area may develop SCC [8-14]. The crack opening area will affect the magnitude of the radionuclide release fraction.

Design mitigation process (e.g., stress relief by heat treatment) may result in the SCC exclusion.

- Cladding failure – Failure could occur by impact stress, creep, or hydrogen embrittlement (e.g., [6] and [15]). Cladding failure may affect the magnitude of the radionuclide release fraction, and may lead to internal structure configuration change.

- Degradation of SNF matrix – Volume expansion associated with the oxidation/hydration of the UO_2 matrix may lead to crack/unzip of defective cladding [16]. The oxidation/hydration may occur with either residual moisture inside the intact canister or from intruded moisture inside the failed canister. This cladding failure may affect the magnitude of the radionuclide release fraction and challenge the retrievability of the SNF materials, and lead to the configurational change in internal structure. The fine-grained and porous rim structure near the cladding of the high burnup UO_2 pellet (above about 60 MWd/MTU) may impact the magnitude of the radionuclide release fraction [6], [17].

- Degradation of neutron absorber – Corrosion of neutron absorbers (e.g., aluminum alloys or borated stainless steel) will affect the effectiveness of nuclear subcriticality control. However, for a criticality event to occur some degree of water moderation would be needed.

5. Two example technical issues

Below describes two specific example issues, which the NRC staff is planning to consider in preparing the risk-informed regulatory bases.

(1) SCC of the stainless steel canister in coastal environments

SCC at of non-stress-relieved welds in a stainless steel canister located in coastal environments may be initiated if the relative humidity (RH) in the air is sufficiently high and the amount of salt deposits is of a sufficient amount to form aggressive and sufficient aqueous conditions. The weld area may have residual tensile stress resulting from the closure welding process. These two conditions of RH and salt deposits are functions of the canister surface temperature. After long time periods, the canister temperature will decrease as the radioactivity inside the canister gradually decays, increasing RH. The temperature, RH and the amount of salt deposits will not homogeneously distribute on the canister surface because the SNF configuration and air flows between the canister and the concrete overpack are not uniform. Considering all these factors, finite probabilities of SCC exists at various times, locations and type of cask designs. The probability could be low enough for SCC to be screened out of a probabilistic evaluation.

When through-the-weld SCC occurs, radionuclide releases may escape the confinement barrier as aerosol driven by the pressure of inert fill gas and fission gas inside the canister. The release rates are affected by the opening area of the canister surface. The SCC area density per weld area of the canister can be estimated conservatively by [18]:

$$\delta = C\,\sigma/E \qquad (1)$$

δ: crack areal density (m^2/m^2)
σ: applied stress (MPa)
E: Young's modulus (MPa)

C: geometric constant

This formula could be applied to the cladding degradation discussed below in the second example issue. An example calculation for stainless steel using equation (1) is the crack mean areal density per unit weld area is approximately $1.2x10^{-3}$ for 170-310 MPa of applied stress, $(193\text{-}207)x10^3$ MPa of Young's modulus [18]. The weld area fraction is about $10^{-2} – 10^{-1}$ [19]. In an example canister surface area of about 30 m^2, the surface opening area will become $3.6x(10^2 – 10^3)$ mm^2. The model in equation (1) is very conservative, assuming a distribution of uniform crack size. In reality, the number and size of cracks are likely to be smaller. This calculated area is obviously larger than that allowed for leak tight [20]. The rate of SCC has not been established.

Through tight cracks, the radionuclide release could be slowed [7,21]. In the aforementioned many computer models for performance evaluation, the cracks formed will lower the magnitude of the radionuclide release fraction, compared with that from bare SNF in the source-term assessment of radionuclide release [22].

In addition to radionuclide release due to SCC, there are other technical issues as aforementioned. The moisture and oxygen will intrude through the cracks into the canister. The UO_2 matrix will be oxidized or hydrolyzed [23-26]. With the volume expansion associated with the oxidation and hydration, initially defective cladding may be cracked or unzipped. This may challenge retrievability of the SNF materials, and may lead to a configurational change in the internal structure. Also, Zircalloy may continue to corrode forming oxide which will also impose stress on cladding. Other internal components may corrode continuously, including neutron absorber, basket materials, and the canister internals. The likelihood of this occurring is very low, because corrective actions should have occurred prior to this stage.

(2) Hydrogen effects on cladding integrity

During reactor operation, the cladding metals, mainly Zircaloy, corrode in the reactor coolant. The corrosion process introduces hydrogen into the Zircaloy. Hydrogen can degrade the strength of Zircaloy by overall embrittlement caused by a dispersion of radially-oriented hydrides (perpendicular to hoop stress) [27]. The hydrides formed during reactor operation are mostly circumferential hydrides (parallel to hoop stress). Circumferential hydrides may not affect the strength significantly, depending on the magnitude of severity. However, circumferential hydrides are known to be radially-reoriented in the presence of appropriate applied stress and temperature [27]. The other hydrogen effects are potential delayed-hydride cracking (DHC). The small cracks developed on the inner or outer surfaces of the cladding may lead to crack propagation assisted by hydrogen diffusion to the crack tip forming radially-oriented hydrides at the crack tip. The mechanism has not been proven to exist under the dry storage conditions, although data are available under reactor operational conditions. If it happens under dry storage conditions, it will likely be limited to higher burnup SNF (e.g., above 60 GWd/MTU). The crack density and size from hydrogen embrttlement of hydride reorientation and DHC can be similarly assessed on a conservative basis as the case of SCC of stainless steel described above in equation (1). The values of crack opening from the model need to be compared with those used in determining the release fraction from experimental work [28]. Lorentz, et al. [28] conducted burst tests by heating a cladded SNF rod, allowing an opening area of about 1.6 cm^2 ($\sim 10^{-1}$ fraction of the total cladding surface). If the calculated value of the opening area by cladding cracking induced by hydrogen embrittlement is smaller than the area used in the independent experiments by Lorenz, et al. [28], the release fraction will not be increased with further cladding cracking by embrittlement. Otherwise, the release fraction from the UO_2 matrix to the canister inside will be affected by the embrittlement. The current regulation for SNF requires that the cladding must be protected during storage against degradation that leads to gross rupture or the SNF needs to be otherwise confined.

Elam, et al. [29] assessed the effects on nuclear subcriticality caused by the configuration changes due to cladding failure. The main assumption in this study is full water flooding in the cask. The report presented the reactivity for various SNF rod conditions. For uniform burnup of 45 and 75 Gwd/MTU collapsed SNF rods, the variations of the neutron multiplication factor, Δk_{eff}, were not significant for this changed cladding configuration.

6. Summary

Some potential technical and environmental issues are discussed, which are associated with uncertainties during long-term SNF storage for up to 300 years. The uncertainties considered are primarily from materials aging. The NRC staff's plan is to incorporate probabilistic risk-informed approaches to confirm the adequacy of the existing regulatory framework or revise the regulatory framework, as appropriate, for long-term SNF storage. This paper addressed:

- Examples of potential technical issues under consideration, including nuclear subcriticality, radionuclide release, radiation shielding, and SNF materials retrievability.

- Methods for performance evaluation to assess the types of risk, including deterministic, and probabilistic risk-informed evaluation under normal accident and natural hazard conditions.

- Consideration of performance evaluation, some potentially important technical issues in the probabilistic risk-informed approach for the canister and cladding integrity. They include mechanical failure of the canister, stress corrosion cracking of the canister, cladding failure, degradation of the SNF matrix, and degradation of neutron absorber. For comparison, the consequence of deterministic approach for these issues are also addressed, as appropriately.

- Two specific example cases, stress corrosion cracking of the canister and cladding failure by hydrogen embrittlement , with respect to radionuclide release and nuclear subcriticality.

The plan to consider the probabilistic risk-informed approach helps ensure a sound regulatory framework remains in place to ensure public health, safety and protection of the environment.

Disclaimer

The NRC staff views expressed herein are preliminary and do not constitute a final judgment or determination of the matters addressed or of the acceptability of any licensing action that may be under consideration at the NRC.

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