Why Risk Assessment in Long-Term Storage of Spent Nuclear Fuel?

T. Ahn, J. Guttmann, and J. Davis

U.S. Nuclear Regulatory Commission (NRC)

Office of Nuclear Material Safety and Safeguards, U.S.A.

For

OECD/NEA Workshop

Safety Assessment of Fuel Cycle Facilities –

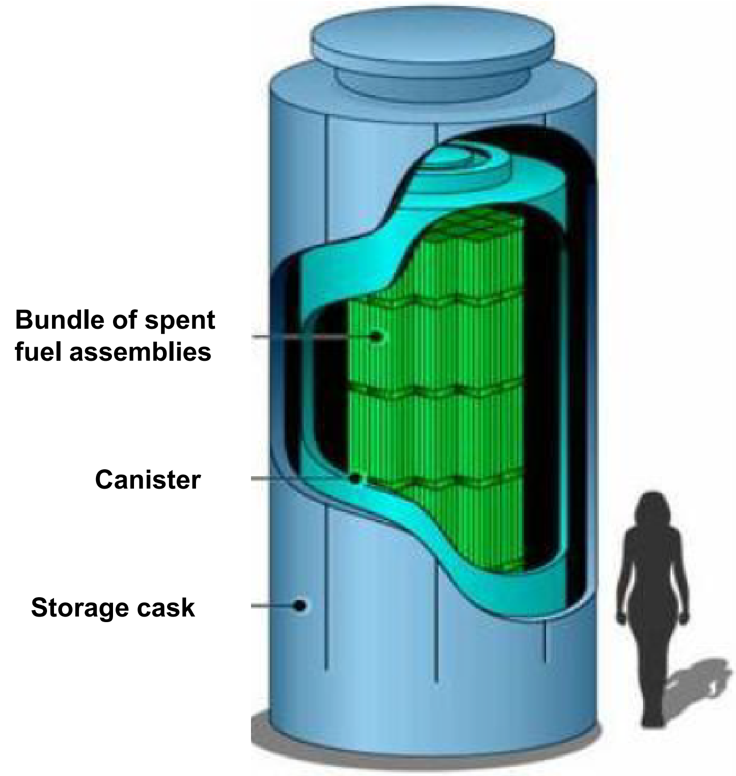
Regulatory Approaches and Industry Perspectives

September 27 - 29, 2011, Toronto, Canada

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.

Cask System
for Spent Nuclear Fuel (SNF) Storage



Introduction

- Presents risk-informed approaches that the NRC staff is planning to investigate in preparing regulatory bases for long-term storage of SNF for extended periods.

- Due to uncertainties associated with long-term SNF storage, it is useful to consider the risk-informed approach in comparison with deterministic design-based approaches.

- The uncertainties considered here are primarily associated with materials aging of the canister and SNF in the cask system under long-term storage conditions.

- Using only deterministic safety assessments to account for potential failure modes associated with all the components of the cask system is difficult and may not address important contributors to safety.

Introduction (continued)

- Discuss some performance criteria and methods of performance evaluation in the risk-informed approach.

- Discuss some potentially important technical issues associated with long-term materials aging for the canister and SNF integrity, and discuss issues in comparison with the deterministic approach, as appropriate.

- Discuss more in detail two example issues, marine stress corrosion cracking (SCC) of the stainless steel canister, and hydrogen embrittlement of Zircaloy cladding, in terms of their potential effects on radionuclide release and nuclear subcriticality, as risk-informed performance measures.

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Introduction (continued)

- The plan to consider the risk-informed approach helps the staff prepare regulatory bases for long-term storage of SNF.
- However, the final regulatory bases must provide reasonable assurance for public health and safety.

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Some Potentially Important Technical Issues Associated with Long-Term Materials Aging

- Three questions on risk: (i) What can go wrong? (ii) How likely is it? and (iii) What are the consequences?

- 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 (e.g., canister monitoring, and site boundary dose assessment)
- 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

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Some Methods of Performance Evaluation of Cask System

- Deterministic modeling techniques, widely used to support design-based regulatory requirements:
- laboratory test results and rigorous numerical modeling in the structural, thermal and criticality assessment
- typically bounding analyses
- consensus standards or regulatory guides

- Probabilistic modeling technique, an extension of deterministic methods:
- 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
- consistent with the risk-informed approach, and enables optimizing and identifying mitigation techniques for the design and operation of the cask system that are a function of the associated risk to the public
- help with the early identification of potentially risk-significant issues

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Some Potentially Important Issues in Canister and SNF

- Mechanical failure of the stainless steel canister:
- mechanical puncture from impact stress will cause canister breach
- cut-off probability is for exclusion
- the breached area affecting the magnitude of the radionuclide release fraction
- a configurational change in internal structure that affects the nuclear subcriticality assessment, and the retrievability of the SNF materials
- the breached canister may or may not be acceptable in the deterministic approach

- SCC of stainless steel canister:
- in a marine (coastal) environment with salt deposits on the canister welds due to salt water droplets in the air
- the crack opening area affecting the magnitude of the radionuclide release fraction
- the design mitigation process for SCC exclusion (e.g., by applying compressive stress), which may be also accepted in the deterministic approach

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

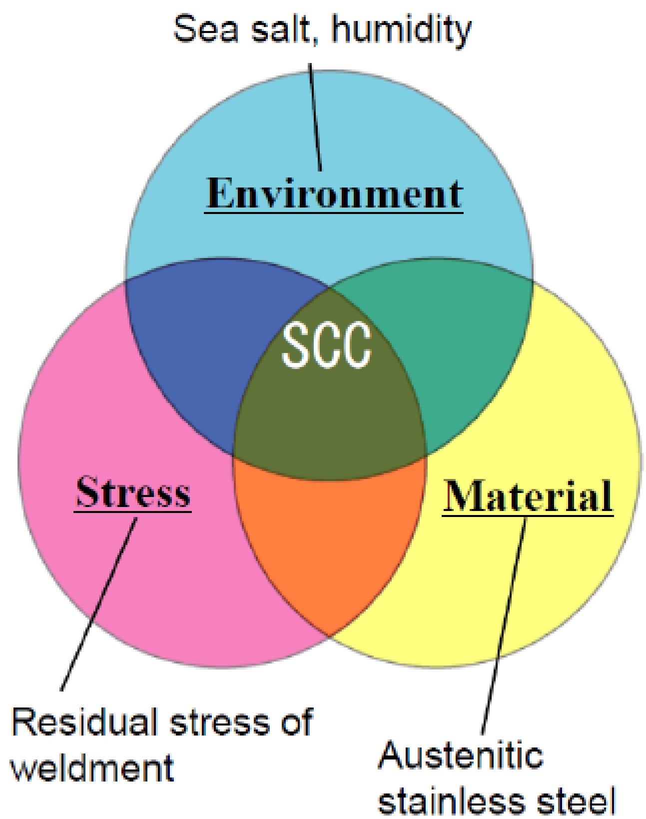
Some Potentially Important Issues in Canister and SNF (continued)

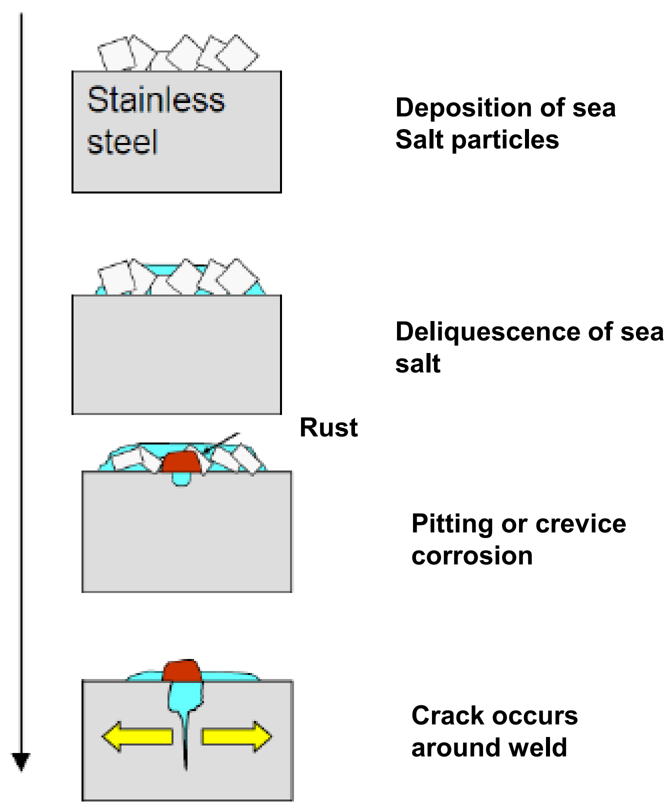
- Cladding failure:
- failure by impact stress, creep, or hydrogen embrittlement
- the crack opening area affecting the magnitude of the radionuclide release fraction and configurational change in internal structure
- In the deterministic approach, this failure may or may not be acceptable (e,g., separate confinement requirement)

- Degradation of SNF matrix:
- volume expansion associated with the oxidation/hydration of the UO_2 matrix, cracking/unzipping defective cladding. The oxidation/hydration may occur with either residual moisture inside the intact canister or from intruded moisture inside the failed canister
- affecting the magnitude of the radionuclide release fraction, challenging the retrievability of the SNF materials, and configurational change in internal structure

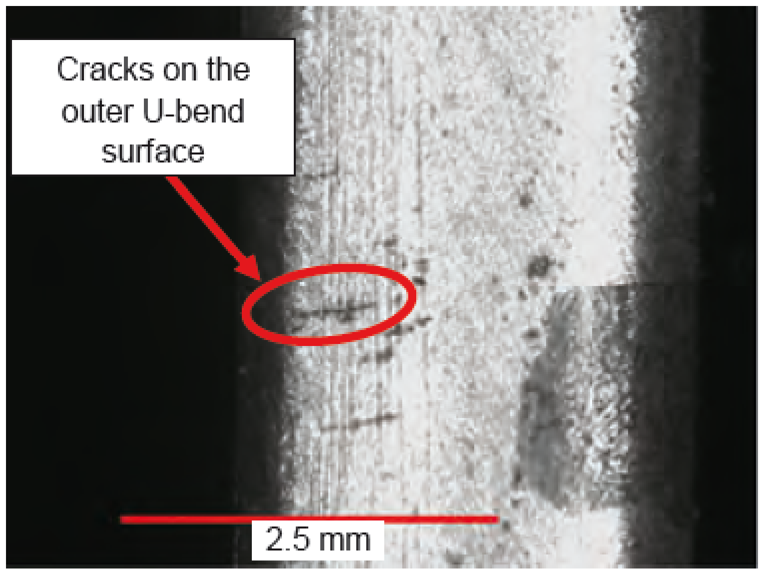
- Degradation of neutron absorber – corrosion of neutron absorbers (e.g., aluminum alloys or borated stainless steel)

Specific Example Case 1: Canister SCC





Specific Example Case 1: Canister SCC (continued)



Typical SCC Behavior of a 304 Stainless Steel Single U-Bend Specimen Exposed for 1 Month at a Temperature of 176 °C [350 °F]

(Caseres and Mintz, NUREG/CR-7030, 2010)

Specific Example Case 1: Canister SCC (continued)

- The SCC of the stainless steel canister is considered when the relative humidity (RH) in air is sufficiently high, the amount of salt deposits is of a sufficient amount, and the surface temperature is low enough to allow deliquescence. This can form aggressive and aqueous conditions at welds to initiate SCC. In longer time periods, the temperature will decrease as the radioactivity inside the canister gradually decays, increasing RH on the outside canister surface.

- The weld area has residual tensile stress remained from the closure welding or fabrication process.

- The SCC area density per weld area:

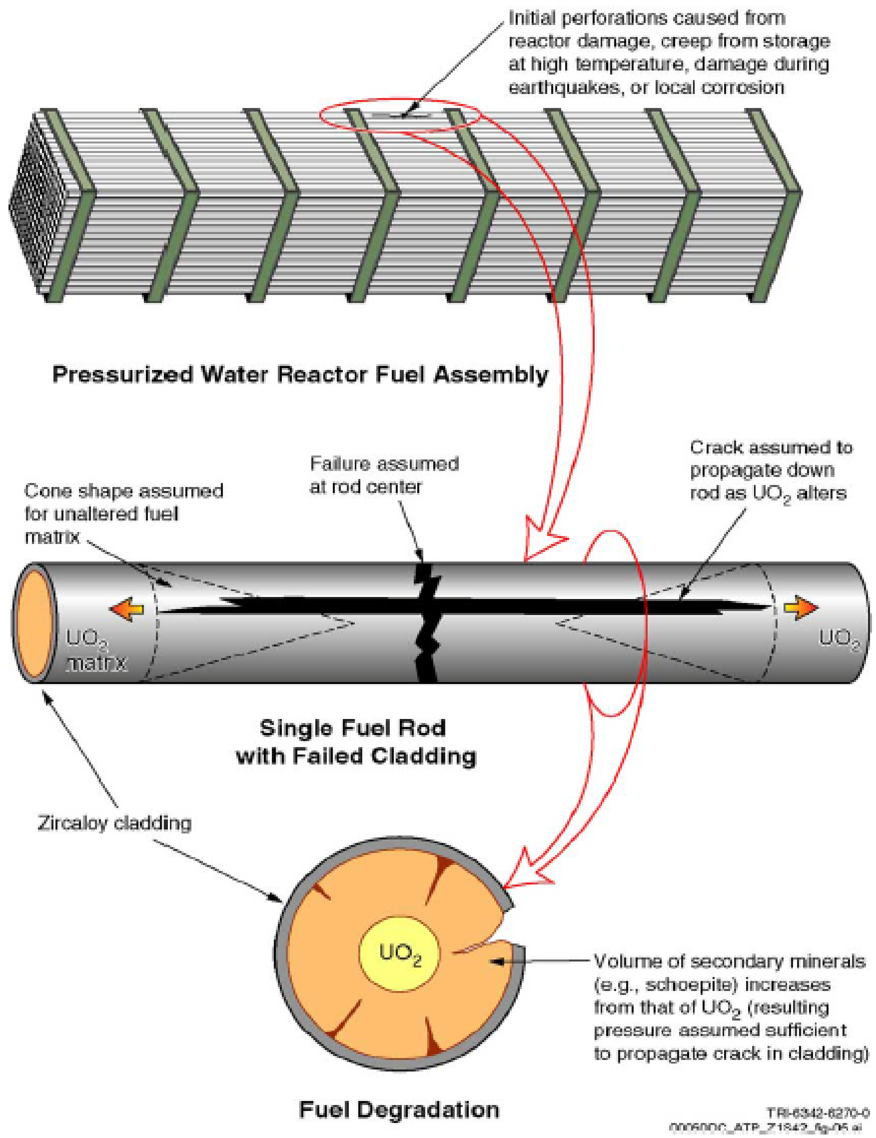
  $\delta = C\ \sigma/E$

δ: crack areal density (m^2/m^2); σ: applied stress (Mpa);

E: Young's modulus (MPa); C: geometric constant

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Specific Example Case 2: Hydrogen effects on cladding integrity



U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Specific Example Case 2: Hydrogen effects on cladding integrity (continued)

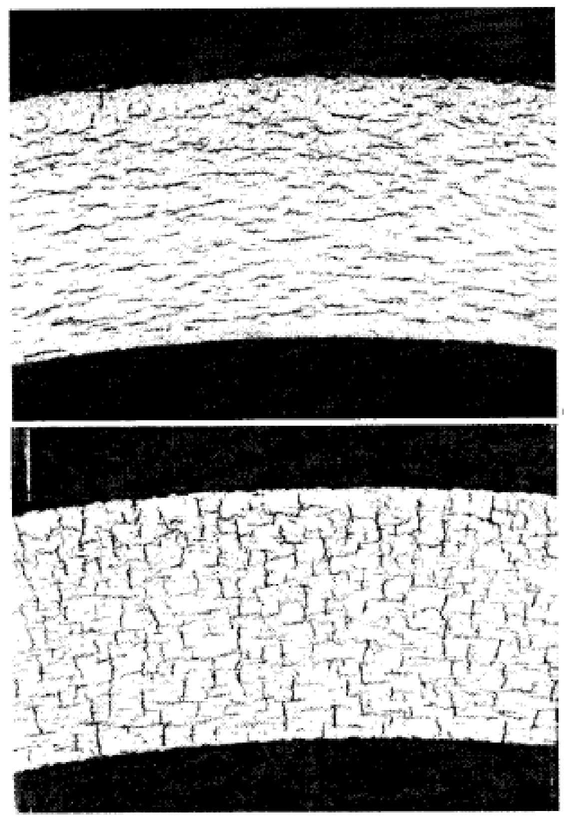
- Hydride reorientaion: circumferential hydrides (parallel to hoop stress of cladding) may be radially reoriented in the presence of appropriate temperature and stress, causing embrittlement.

- Delayed-hydride cracking: the small cracks developed on the inner or outer surfaces of cladding, leading to crack propagation assisted by hydrogen diffusion to the crack tip forming radially-oriented hydrides at the crack tip.

- Nuclear criticality caused by the configuration changes due to cladding failure seems to be controlled from model studies.

Specific Example Case 2:
Hydrogen effects on cladding integrity(continued)

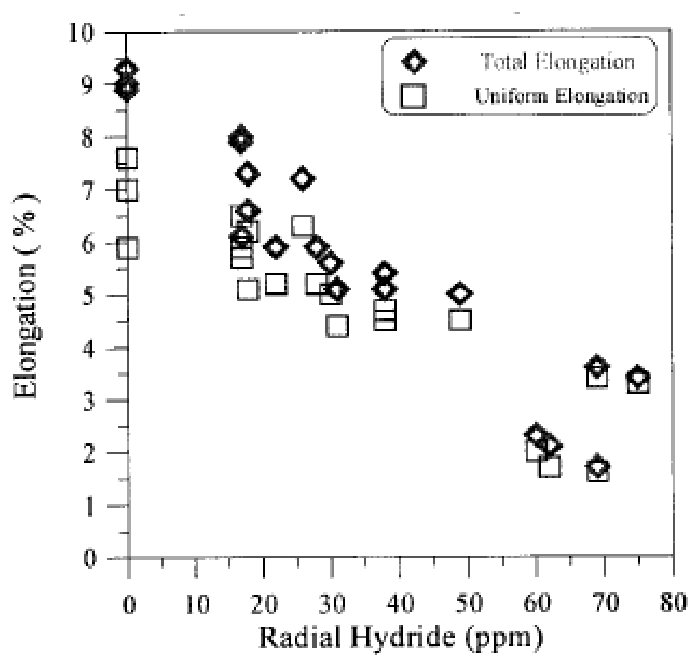
Hydride reorientation
from circumferential (a) to
radial (b)
direction to hoop stress
(Yagnik, et al., 2004);
cladding thickness of ~0.6
mm


(a)
(b)

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Specific Example Case 2: Hydrogen effects on cladding integrity (continued)

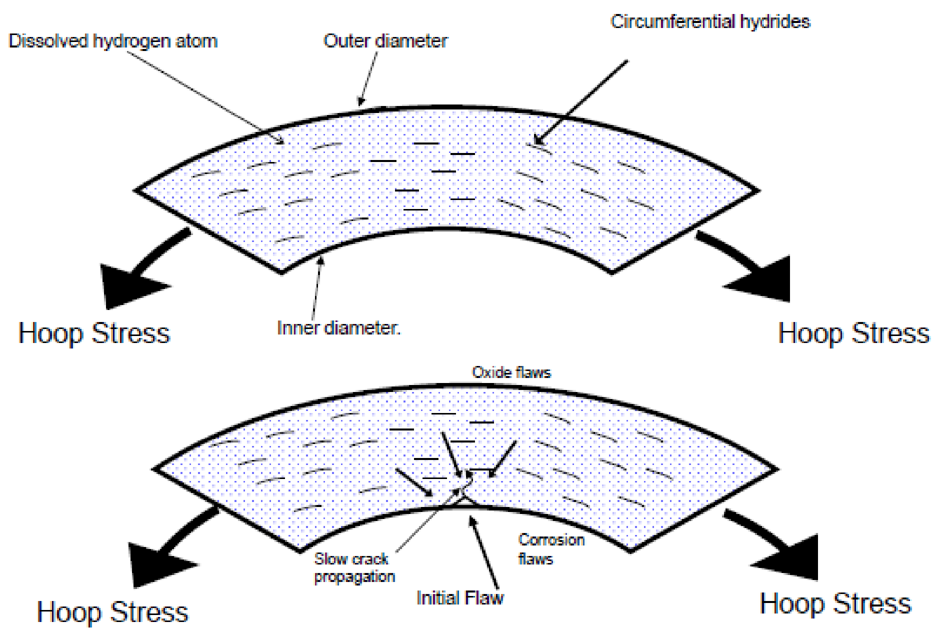
Effects on mechanical property, ductility loss



(Yagnik, et al., 2004)

Specific Example Case 2:
Hydrogen effects on cladding integrity (continued)

Delayed-hydride cracking



U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Summary

- Some potential technical and environmental issues are discussed, which are associated with uncertainties during long-term SNF storage. The uncertainties considered are primarily from materials aging, and the risk-informed approaches are emphasized in identifying potential issues.

- The paper addressed: types of potential risk, methods for performance evaluation, and some potentially important technical issues in the risk-informed approach for the canister and cladding integrity. For comparison, the deterministic approach for these issues are also addressed, as appropriate.

  Two specific example cases were illustrated, for canister SCC and cladding failure by hydrogen embrittlement, with respect to radionuclide release and nuclear subcriticality.

- The plan to consider the risk-informed approach helps the staff prepare regulatory bases for long-term storage of SNF. However, the final regulatory bases must provide reasonable assurance for public health and safety.