Cladding Failure Resulting from Chloride-Induced Stress Corrosion Cracking in Dry Cask Storage System Canisters

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INTRODUCTION

Several in-service Dry Cask Storage System (DCSS) designs in the United States utilize an austenitic stainless steel confinement canister within a concrete shielding structure for storage of spent nuclear fuel.

Austenitic stainless steels are known to be susceptible to stress corrosion cracking (SCC) in a chloride environment when tensile stresses are present. Under normal conditions of storage, the confinement integrity of the canister must be maintained over the duration of storage, including the initial licensing period (40-year maximum) as well as any subsequent license renewal periods (40-year maximum increments) to prevent oxidation of any damaged fuel or fuel with cladding pinholes.

If an SCC crack penetrates the canister, eventually oxygen will enter resulting in subsequent oxidation of the UO_2 fuel pellets which may result in degradation of the fuel cladding by splitting. The amount of time required before cladding degradation is realized (t_{clad}), requires consecutive events to occur:

$$T_{clad} = t_{SCC} + t_{depressure} + t_{diffuse} + t_{oxy} \quad (1)$$

Where t_{SCC} is the time for a through wall SCC crack to develop; $t_{depressure}$ is the time to depresssurize the canister; $t_{diffuse}$ is the time to diffuse sufficient oxygen into the canister to oxidize the fuel; and t_{oxy} is the time to oxidize the fuel and split the cladding.

ASSESSING CLADDING INTEGRITY

SCC Initiation

The total time to have a through wall breach (t_{SCC}) consists of an initiation time (t_{init}), and a propagation time (t_{crack}).

Once the storage canister is placed in service, the time required to initiate chloride-induced SCC on the canister's external surface (t_{init}), would depend primarily upon alloy type, temperature, relative humidity, stress state of the metal and areal chloride concentration. SCC initiation requires a specific material, tensile stress, and environmental conditions. Removing any one of these parameters will eliminate the need to consider this failure mechanism and would be the most robust method of addressing SCC concerns.

Regions of tensile stress exist on DCSS canisters during normal storage conditions as a result of applied, residual, and thermal loads. Residual tensile stresses are expected to be highest in the DCSS canister weld metal but have not been quantified.

Accumulated surface chloride from the atmosphere must deliquesce, or absorb moisture from the atmosphere, before the underlying stainless steel becomes susceptible to SCC. Testing has demonstrated SCC in austenitic stainless steels exposed to a bounding cyclic humidity environment at 43ºC (109ºF). However, SCC did not occur at or above 85ºC (185ºF) due to a lack of salt deliquescence. [1] The current maximum threshold temperature of 85ºC (185ºF) can be used along with service temperature data to determine whether a specific canister is susceptible to SCC.

DCSS canisters that accumulate a higher areal concentration of chlorides are expected to have an increased susceptibility to SCC. However, local chloride accumulation is difficult to determine. As an initial step, methods to collect data from in-service canisters are under development. Laboratory tests can also be used to estimate accumulation rates. [2]

SCC Crack Growth

The initial SCC crack must grow through the wall of the DCSS canister. The time required to breach the canister wall, t_{crack}, would depend on the initial crack size, orientation, stress field and temperature. Crack growth measurements of austenitic stainless steels are well documented under various conditions in literature, but conditions similar to those seen by the DCSSs are not well characterized.

Helium Depressurization

After breach of containment, the helium backfill within the canister has to depressurize to reach equilibrium with the ambient environment. The time to depressurize, $t_{depressure}$, would depend primarily on the size of the through-wall crack, the thickness of the canister wall and the gage pressure within the canister.

Oxygen Diffusion

After the internal pressure of the DCSS canister has equilibrated with the ambient environment, subsequent diffusion of oxygen into the canister will occur. The time required for oxygen to diffuse into the canister and further oxidize the UO_2 to $UO_{2.4}$, $t_{diffuse}$, would depend on the size of the crack, the O_2 partial pressure differential of the canister, burnup of the fuel, and the environment and temperature.

Fuel Oxidation

The time required for oxidation from $UO_{2.4}$ to U_3O_8, t_{oxy}, and subsequent cladding degradation is dependent on the oxygen concentration within the canister and temperature of the fuel pellets. The transformation to U_3O_8 occurs with ~33% lattice expansion that induces a circumferential stress in the cladding. The cladding strains due to this stress range from 2-6% before the initial crack starts to propagate along the fuel cladding. The incubation time to initiate the propagation and the rate of propagation has an Arrhenius temperature dependence. [3]

RESULTS

An equation was developed to estimate the time to cladding failure, assuming SCC in a DCSS canister. The parameters in the equation have been evaluated to determine the rate limiting steps and the conditions under which SCC of the canister might not be consequential. Uncertainties in the t_{clad} based on uncertainties in the input values to the equation were highlighted as potential areas for further research.

REFERENCES

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