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ABSTRACT

The conditions of continued dry storage of the spent nuclear fuel in multipurpose canisters render the canisters, a component for confinement in dry storage cask systems, susceptible to chloride-induced stress corrosion cracking (SCC). The requisite conditions involve deposits of chloride-bearing marine salts and/or dust that deliquesce on the external surface of the cooling canister to create brine at weld residual stress regions. The subcritical crack growth rate at this “dry salt” condition, investigated by several researchers, has shown a relatively slow growth rate compared to chloride-cracking under aqueous conditions. A new SCC growth rate test specimen configuration has been developed to enable an initially dried salt assemblage to deliquesce under temperature and humidity conditions to load the fatigue pre-cracked, wedge-opening-loaded (WOL) specimen with the brine and enable measurements of crack growth rate (da/dt) under falling stress intensity factor, K, conditions. The application of the results to a canister weldment with a residual stress profile to predict crack extension in time is described. The results are evaluated in terms of development of acceptance standards for this type of flaw, should SCC be identified and characterized through inservice inspection (ISI).

INTRODUCTION

Many dry cask storage systems for spent nuclear fuel are of a dry shielded canister (DSC) design that includes a welded construction (and weld-sealed) austenitic stainless steel multipurpose canister that is placed within a concrete overpack and stored on an outside pad. Tests and experiments have shown that stainless steels typical of those used for the canisters (e.g. 304, 304L, 316, or 316LN) are susceptible to stress corrosion cracking with chloride-containing salts [1-5]. The degradation scenario is that chloride-rich salts and other debris deposit on the canister through atmospheric convection over time and, if the local relative humidity at the canister surface is “high,” deliquesce to form a moist salt or brine. The wetted chloride salt deposit is aggressive to stainless steel for pitting and cracking corrosion, particularly at weld heat-affected-zone regions with sensitized microstructures and residual stresses.

No observation or evidence of pitting or cracking attack of canisters due to corrosion has been observed to date. Nevertheless, the U.S. Nuclear Regulatory Commission is requiring that the dry storage licensee institute an Aging Management Program (AMP) to demonstrate that the structural integrity and confinement function of the canisters is maintained for extended (re-license) storage conditions in consideration of the potential for SCC [6]. Consensus rules for inservice inspection of the canisters are being developed, and these rules can serve as the foundation for the canister AMP. A Task Group was constituted in 2015 under Section XI, Division 1 of the ASME Boiler and Pressure Vessel Code to draft a new Code Case N-860, “Examination Requirements and Acceptance Standards for Spent Nuclear Fuel Storage and Transportation Containment Systems.”
Flaw acceptance criteria are needed for the disposition of the inspection results should relevant indications be found during the examination. Disposition of flaws that would be identified as stress corrosion cracks, and characterized or sized using visual, surface, and volumetric examination methods requires, as inputs to the technical bases, both evaluation of flaw stability under design basis loading cases, and also allowance for flaw growth between inspection intervals. Even if shown as mechanically stable, through-wall flaws would not be acceptable due to their challenge to the confinement function of the canister.

The stability of flaw postulates, both parallel and perpendicular to circumferential (girth) and longitudinal (axial) canister weldments has been reported in several studies. Canister-specific dimensions, material properties, and loading conditions, were applied in flaw stability analyses using ASME SCXI [7] for the limit-load method [8], and using API/ASME Level 2 assessment [9] for the failure assessment diagram (FAD) method [10] with welding residual stress profiles estimated from the ASME/API methodologies. Work presented at this conference [11] compares the flaw tolerance in stainless steel piping (Nominal Pipe Size 32-inch with 0.75-inch wall thickness) using Nonmandatory Appendix C (Article C-5000 limit load criterion and also Article C-6000 elastic-plastic fracture mechanics criterion), and Nonmandatory Appendix H (FAD) methods under ASME SCXI. The common conclusion is that the static, low loading conditions of the austenitic stainless steel canister is highly tolerant of flaws. However, it is observed that with the residual stress included as part of the loading, and with the consideration of elastic-plastic fracture mechanics through the FAD formulation, the instability crack sizes are significantly reduced from those based on the net section yielding limit load failure criterion [10]. The instability crack sizes (length and depth) for more realistic, semi-elliptic surface crack configurations were also presented at this conference [12] using R6 Option 1 FAD procedure [13] and the through-wall welding residual stress distributions used in Reference [10].

Results vary widely among the available literature on crack growth rate (CGR) testing under conditions relevant to the deliquescing salt conditions on the canister. This appears to be due, in part, to the difficulty in establishing a crack growth front in a test specimen subject to a constant, controllable salt brine condition. This paper presents the design of a new “dry salt” SCC specimen test configuration to overcome that limitation. The test specimen configuration provides a crack growth rate test specimen charged on the edge of the crack plane with an initially-dry salt assemblage that would deliquesce under temperature and humidity conditions and thereby environmentally load a fatigue pre-cracked, wedge-opening-loaded specimen with the naturally-formed brine. The specimen design and test configuration enables measurements of crack growth rate (da/dt) under falling stress intensity, Kf conditions (the falling K is caused by compliance change due to crack growth under constant crack opening displacement, or COD, loading). This data would be applied to estimate subcritical crack growth in the residual stress fields of canisters weldments.

CRACK GROWTH KINETICS

Deposits on the surface of a DSC, especially those near a seacoast with a source of atmospheric marine salts, or an industrial setting with a source of fly-ash particulates, could be anticipated to be a mixture of dust and chloride-bearing salts and compounds. The initiation of stress corrosion cracks with these deposits is dependent on the salt/dust assemblages, temperature and humidity, and the material and its surface stress condition [1-5]. Further considerations of the requisite conditions and the timeframe of the potential initiation of cracks are not developed in this paper.

If a flaw in a canister has been identified as a stress corrosion crack with consensus NDE (nondestructive examination) methods and qualified inspection personnel, the characterization of the flaw and an understanding of its likelihood and rate for further propagation are needed for its disposition.

There are several specimen designs and approaches to test (measure) crack velocity or da/dt under a stress intensity factor, K, loading. Figure 1 shows the various geometries and loading modes for the crack growth rate test specimens.

PRECRACKED SPECIMEN GEOMETRIES FOR STRESS CORROSION TESTING

FIGURE 1  PRECRACKED SPECIMEN GEOMETRIES FOR STRESS CORROSION TESTING (figure from the United States Naval Research Laboratory, Washington, DC)
The challenge with generating data relevant and directly applicable to the DSC is the environmental loading and testing for what we will call “dry salt” conditions. That is, with initial fully dried deposits on the canister surface, and under falling canister temperatures with extended times, the deposits with deliquescing salts will create the aggressive environment.

Crack growth rate testing aimed at conditions for a DSC in natural exposure settings and with salt assemblages loaded onto the specimens has been performed over the past several years. Researchers at Japan’s Central Research Institute of Electric Power Industry have generated the largest data sets to date [5, 14-17]. The specimen designs included 4-point bend [3], 3-point bend [15, 16], and compact tension (CT) [14, 17]. Figures 2 to 4 show a sampling of the specimen designs and mechanical loading with the corresponding crack growth rate results.

**FIGURE 2  4-POINT BEND TEST SPECIMEN CONFIGURATION AND RESULTS (Reproduced from [3], the specimen may not have contained a pre-crack)**

**FIGURE 3  CT TEST SPECIMEN CONSTANT LOAD CONFIGURATION AND RESULTS (Reproduced from [14])**
Specimens can be tested without pre-cracks, however pre-cracks are typically used to provide a defined initial crack front in a specimen. Semi-elliptical cracks can be electro-discharge machined (EDM) in the 4-point bend specimen design, although it appears that this was not used in the CRIEPI testing in Figure 2 based on the cross-section containing the SCC [3]; fatigue pre-cracking in air was not always used in the testing with 3-point bend [15,16] and CT [14] design specimens in the CRIEPI testing. The aggressive environmental conditions used to load the crack growth test specimens was chloride solutions or artificial seawater. Natural exposure testing was also used in the 3-point bend specimen testing [15,16].

For the CT testing, the chloride solution was placed as droplets (~20 µL) at the pre-crack region [14] of the specimen and allowed to dry. The specimen was then exposed to temperature and humidity conditions.

Phenomenologically, stress corrosion cracking typically has a dependency on the applied stress intensity factor, K, as shown in Figure 5. A threshold stress intensity factor, $K_{SCC}$, is observed below which SCC does not propagate and/or propagates very slowly and would not grow to threaten the structural integrity of a component over its lifetime. A region of crack growth occurs that is relatively insensitive to the K loading, followed by a region of strong dependency of subcritical crack growth on K prior to mechanical instability. The mechanical instability is the classic intrinsic fracture toughness of the material, conventionally labeled as $K_C$.

Ideally a test configuration would allow salt loading to be prototypic to the canister in that it is initially a dried salt assemblage with dust or inert material. The salt would be allowed to deliquesce under the test conditions of temperature and humidity to form brine that could be drawn by capillary forces to the crack tip. Further, the configuration would allow the characterization of the K dependency in a single test setup. A new test configuration, described in the next section, has been developed at the Savannah River National Laboratory; the testing is being initiated at the time of this paper.

![Figure 4: 3-Point Bend Test Specimen Configuration and Results](image)

![Figure 5: Example SCC Growth Dependency on Applied K](image)

**Materials:** 304 and 304L

**Natural Exposure (Miyakojima Island):**
- CGR: $1.2 \times 10^{-12}$ to $1.8 \times 10^{-11}$ m/s
- $= 0.04$ mm/yr to 0.5 mm/yr

**Accelerated Test (60°C, 95RH, NaCl steam mist):**
- CGR: $1.0 \times 10^{-10}$ to $3.5 \times 10^{-9}$ m/s
- $= 3$ mm/yr to 110 mm/yr

**FIGURE 4 3-POINT BEND TEST SPECIMEN CONFIGURATION AND RESULTS (Reproduced from [15, 16])**

**FIGURE 5 EXAMPLE SCC GROWTH DEPENDENCY ON APPLIED K (the SRNL data shown is for A285 carbon steel under conditions of nitrate stress corrosion cracking [18])**

**DRY SALT CRACK GROWTH KINETICS - WEDGE OPENING LOADED SPECIMEN DESIGN**

Figure 6 shows the sketch of the new dry salt SCC test configuration concept that uses a wedge opening loaded specimen per ASTM E1681, “Standard Test Method for Determining Threshold Stress Intensity Factor for...”
Environment-Assisted Cracking of Metallic Materials,” that is loaded with an instrumented bolt, and that contains a special cradle to load a salt mixture and hold it against the external faces of the specimen. The SCC testing is under “falling K” kinetics that would provide data to enable construction of a da/dt vs K curve such as shown in Figure 5. Since the strict dimensions to enable plane strain conditions in the specimen design with austenitic stainless steel are not met, the derived K is termed KJ to reflect that plastic conditions exist at the crack tip in the testing.

Figure 7 shows the actual test assembly that has been constructed for this concept. The glass vessel shown would contain brine following ASTM E104, “Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions,” at the bottom of the vessel to control the relative humidity (RH) at a desired target level (e.g. MgCl2 to control RH at 30%). The vessel is placed in an oven for temperature control. The feed-through on both the glass vessel and the oven enable a DAS to acquire load drop with time for a fixed displacement (COD). The ASTM-based algorithms are applied to estimate the crack length and applied K real time. Post-test visual check of the crack lengths on the sides of the specimen, and also the specimen crack face with destructive examination will validate and calibrate the estimations.

The salt mixture cradle is machined from an aquarium bubbler, and its porosity allows a humid air contact to the salt mixture. The test salt assemblages are 1) CeO2 + 2% mixture of NaCl/KCl/CaCl2 and 2) a mixture of dust and artificial sea salt. The temperature and humidity conditions are 45 ºC and 30-50% RH, respectively. The testing is being conducted to shakedown the test configuration before a set of test conditions are selected by an inter-laboratory research team.

APPLICATION OF DRY SALT CRACK GROWTH DATA FOR FLAW DISPOSITION IN ISI

As stated, flaw growth must be considered in disposition of flaws identified and characterized in inspection of a DSC. There are two primary inputs for planar flaw growth evaluation, namely:

(1) residual stress distributions for canister fabrication welds1; and
(2) crack growth rate curve(s) or da/dt vs. K for these canister materials and environmental conditions

Estimation of weld residual stresses for a DSC has been performed using the methodology contained in reference [9]. The full results have been reported in reference [10]. As an example, Figure 8 shows the calculated through-wall residual stress distribution perpendicular to a circumferential weld. Measurements of the weld residual stresses on a full-size prototype DSC are in progress at the Sandia National Laboratory [19].

1 Applied loads need to be checked for role in subcritical flaw propagation.
Appendix C of the ASME SCXI provides guidance for evaluation of crack growth for light-water reactor (LWR) conditions. The guidance from Appendix C can be used in evaluation of flaw growth under dry salt SCC conditions. Figure 9 is the da/dt vs K crack growth model recommended in Appendix C. It is expected that the new testing underway, and with the other literature data will be assembled to construct a recommended SCC growth rate curve (da/dt vs. K) for the N-860 code case.

The available data to date on SCC under “dry salt” conditions, especially the CRIEPI data [16] under natural conditions, suggest that a constant rate of 0.5 mm/year represents the crack growth rate for a range of K loadings. This rate is recommended to be used to estimate SCC growth in the interim until additional testing and consensus evaluation of the data is complete, and the results are published in code case N-860.

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FIGURE 8 CIRCUMFERENTIAL CRACK PARALLEL TO A CIRCUMFERENTIAL WELD - RESIDUAL STRESS PERPENDICULAR TO THE DOUBLE-V NOTCH CIRCUMFERENTIAL WELD (Reproduced from [10])

FIGURE 9 da/dt vs K for Intergranular Stress Corrosion Cracking (Reproduced from [14] and curve from NUREG-0313 [20] and ASME SCXI, Non-mandatory Appendix C [7])
REFERENCES


