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A numerical investigation of the mechanical response of dual-purpose canisters to internal pressurization

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DISCLAIMER

This is a technical paper that does not take into account contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (10 CFR Part 961). For example, under the provisions of the Standard Contract, spent fuel in multi-assembly canisters is not an acceptable waste form, absent a mutually agreed to contract amendment. To the extent discussions or recommendations in this paper conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this paper in no manner supersedes, overrides, or amends the Standard Contract. This paper reflects technical work which could support future decision making by the Department of Energy (DOE). No inferences should be drawn from this paper regarding future actions by DOE, which are limited both by the terms of the Standard Contract and a lack of Congressional appropriations for the Department to fulfill its obligations under the Nuclear Waste Policy Act including licensing and construction of a spent nuclear fuel repository.

1 INTRODUCTION

Storage, transportation, and long-term disposal of spent nuclear fuel (SNF) is an on-going challenge in many countries. Around 20% of the electricity generated in the United States is from nuclear power plants. These plants generate around 2,000 metric tons-uranium (MTU) of SNF annually and there is presently an inventory of more than 80,000 MTU, of which approximately 30,000 MTU are in dry storage. Dual purpose canisters (DPCs) are widely used for dry storage, and for transportation (where certified) of SNF assemblies. The U.S. Department of Energy, Office of Spent Fuel and Waste Science & Technology is investigating the technical feasibility of direct geological disposal of SNF in loaded DPCs. Because DPCs, and in particular the neutron absorbers, were not designed for geologic disposal, post closure criticality control is an important aspect of this investigation. Over geological timescales, it is probable that the canister and its disposal overpack would eventually be breached by initial cracks (fractures) due to stress corrosion cracking or other corrosion processes. A breach in the canister could allow ground water to fill the void space around the fuel, in repository settings that are either unsaturated or saturated (above or below the water table). If the canister internals including neutron absorber components are sufficiently degraded by exposure to ground water, a criticality event could occur. Such an event would create transient elevated temperature and pressure conditions within the DPC and overpack. This internal pressurization could cause the initial fractures in the canister shell and overpack to deform and grow, affecting hydraulic transmissivity with the surroundings, and displacing water or steam from the waste package. It is important to understand the change in transmissivity for two reasons. First, it could have significant influence over the nature of criticality events including their energy and repeat frequency, and secondly, because it will control the release of radionuclides from the canister.

2 MODELING METHODOLOGY

The modeling assumes that the canister has an initial breach (crack) in both the canister and overpack, and that the canister is filled with water. *FLAC3D* (Itasca 2017) is used to model deformation, yielding and fracturing of the canister and overpack. Figure 1 shows a schematic of the model. Four model geometries are considered: two cases with a longitudinal fracture and two cases with a hoop fracture. For each fracture orientation, two fracture locations are considered: one in the middle of the canister and one near the base of the canister. For each geometry three different values of initial fracture length are considered. For each geometry and fracture length, two canister thicknesses are considered: 1.2 cm to represent the canister and 2.45 cm to represent the overpack. The model does not represent the canister and overpack simultaneously; each component is considered separately.

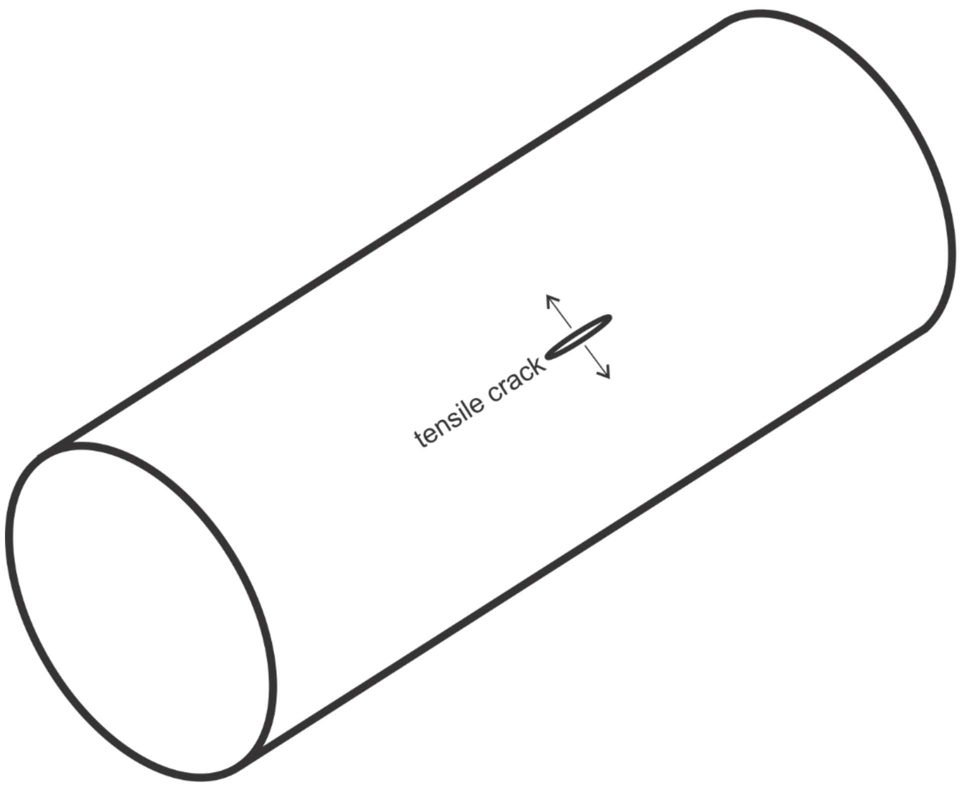

Figure 1. Schematic of waste package breach model.

The models are quasi-static, which means they represent slower behavior and that inertial effects on the deformations are neglected for simplification. A spatially uniform and time-constant pressure is applied to the inner surface of the canister (this is the differential of internal minus external pressures). The model is solved to equilibrium. This analysis considers the limiting case where pressure is constant for long enough to cause fracture growth or other failure in the canister. Once mechanical equilibrium is reached at a given pressure, the pressure is increased, and mechanical equilibrium is reestablished. The model is stopped when the critical pressure (that causes canister failure) is reached. The difference between canister and overpack behavior is addressed by using a range of values for wall thickness, which effectively assumes that one breach or the other will dominate transmissivity with the surroundings, and can be tested in later model development.

In the present modeling both the canister and the overpack are assumed to be made of stainless steel with the same properties. The properties typical for stainless steel were used in the analysis. The elastoplastic response of steel is represented by the von Misses criterion. Two ultimate strengths were assumed in the analysis because of elastic-perfectly plastic approximation. One, 300 MPa, is the mean of the actual yielding and ultimate strengths of stainless steel. The second, 445 MPa, is the ultimate strength of stainless steel. The ultimate strength is considered relevant for canister failure as a result of yielding and necking. It is assumed that propagation of the initial crack is in Mode I (i.e., opening) and governed by linear elastic fracture mechanics (LEFM). Mode I fracture toughness, K_{IC}, for stainless steel can vary between 40 and 100 MPa×m$^{1/2}$. The value of 50 MPa×m$^{1/2}$ is assumed for K_{IC} of the stainless-steel material (Matthews 1973) of the canister and overpack.

Modeling fracture propagation numerically presents significant challenges and can be computationally intensive. In this study, it is assumed that fracture will propagate along the specified trajectory (i.e., predefined fracture surface). A *FLAC3D* interface along the assumed path of fracture growth is explicitly introduced into the model geometry and is bonded initially. The orientations of the stress tensors indicate that the assumptions of the fracture propagation trajectories (i.e., straight along the canister and straight in the hoop direction) are correct for all analyzed initial crack configurations.

The condition of the fracture propagation was determined using the LEFM. The approximation by the LEFM is justified because the process zone for the assumed steel properties is estimated, $l = (K_{IC}/\sigma_Y)^2/\pi$, to be approximately 1 to 3 mm, which is relatively small compared to the assumed initial crack lengths for which the canister failure is controlled by fracture propagation. The tensile strength of the interface is calculated such that the fracture toughness, K_{IC}, is represented correctly, using the following relation:

$$K_{IC} = \alpha\, \sigma_t \sqrt{\delta}$$

where α is a dimensionless quantity with value near one, σ_t is the tensile strength and δ is the *FLAC3D* interface element length. From the above equation, the numerical value of fracture toughness depends on discretization, i.e., zone size. Therefore, to match the fracture toughness, tensile strength must be selected based on the zone size.

3 RESULTS AND DISCUSSION

3.1 *Critical Pressure for Steel Yielding*

Before presenting the results of the numerical analysis it is worth considering the expected critical pressure for yielding in an infinitely long steel cylinder. Failure of the canister due to plastic yielding (without pre-existing crack) occurs when internal pressure reaches the critical value given by the following relation:

$$P_c = \frac{\sigma_y t}{r}$$

where P_c is the critical pressure, σ_y is the steel yield strength, t is the canister thickness, and r is the canister radius. The canister of 1.2 cm thickness yields at a critical pressure of 4 MPa and the overpack of 2.5 cm thickness yields at a critical pressure of 8.4 MPa. This is relevant because fractures cannot grow if plastic yielding happens first. (Considering perfectly plastic behavior of steel, yielding of the canister is also failure of the canister.) The axial stress due to pressurization of the canister lids is less than the hoop stress. It is expected (see yielding pressures in Figures 3 and 4) that the actual internal pressure at canister failure due to plastic yielding will be higher because of the influence of the ends of the cylinder.

3.2 *Numerical Model Results*

Two failure criteria are possible for both the canister and overpack: fracture propagation and plastic yielding. To accommodate both failure modes each model is run twice: (1) using an elastic constitutive behavior for the steel and a LEFM criterion for fracture propagation, and (2) an elastoplastic criterion for the steel, without an initial fracture. These models must be run separately because the plasticity occurring in the coarse mesh is over a larger length than the expected fracture process zone of 1 to 3 mm. To represent fracturing in *FLAC3D*, the plasticity in the process zone is implicitly represented in the Mode I fracture toughness value and local plastic dissipation is not explicitly represented in the model. Further, the LEFM solution is suitable in this case because the initial fracture lengths are an order of magnitude larger than the expected process zone size. The model that fails at the lowest pressure is considered the dominant mechanism for that configuration. Figure 2 shows a typical result for displacement in the longitudinal fracture cases. Figures 3 and 4 show calculated critical pressures for the longitudinal and hoop fractures, respectively. The orange curve shows the fracture propagation criterion and the blue curve shows the plastic yielding criterion. Whichever is lower happens first and suppresses the other mechanism. The results are presented as composite curves in which the solid line indicates the behavior. A dashed line is plotted when the critical fracture propagation pressures are above the yield strength.

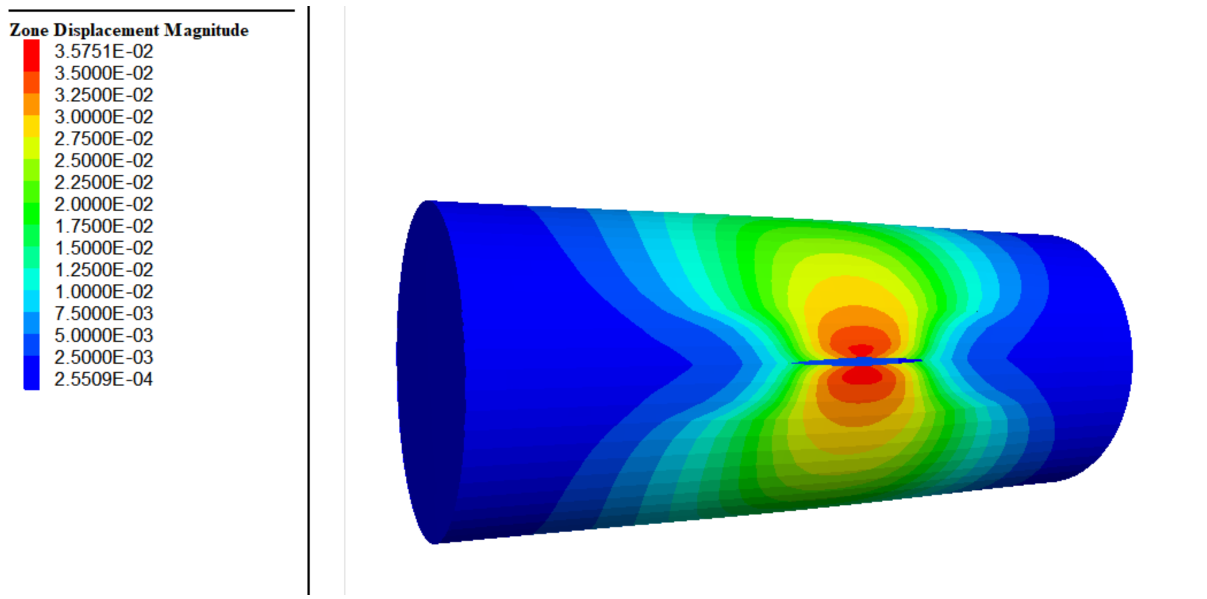

Figure 2. Typical results (displacements magnitude contours in meters) for a longitudinal fracture.

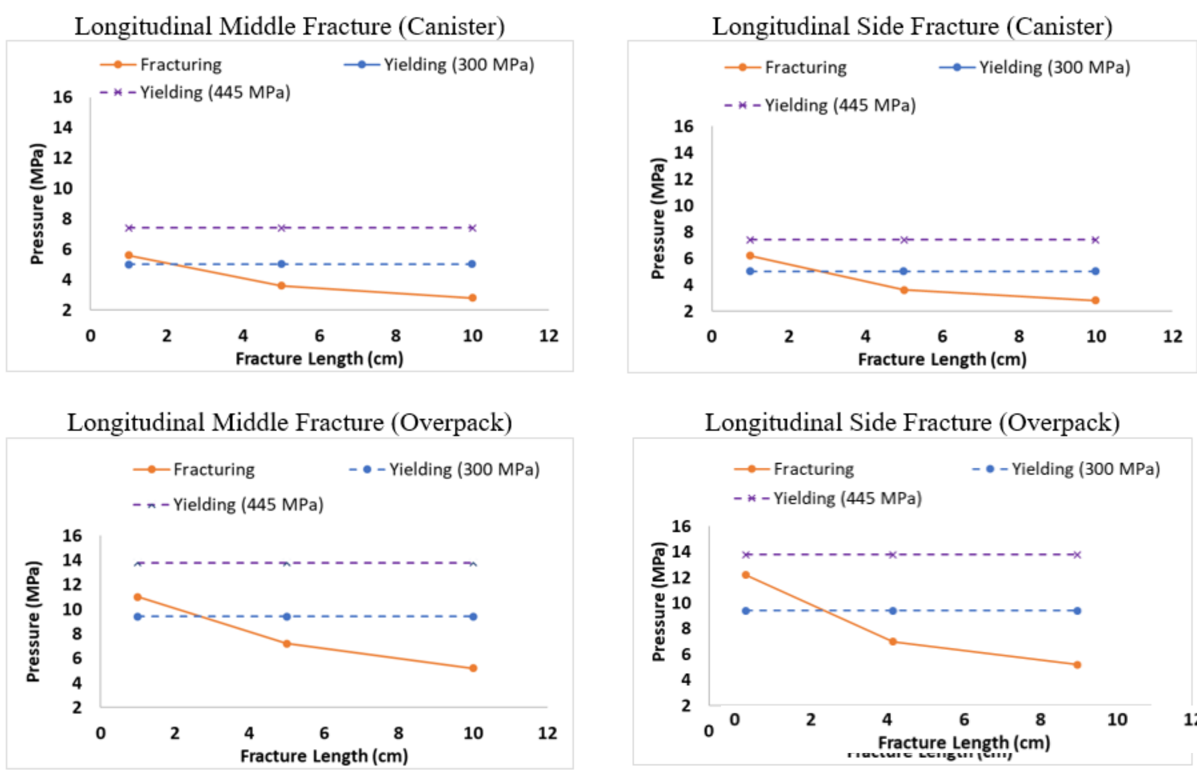

Figure 3. Critical pressure for longitudinal fractures of different lengths in both the canister and the overpack.

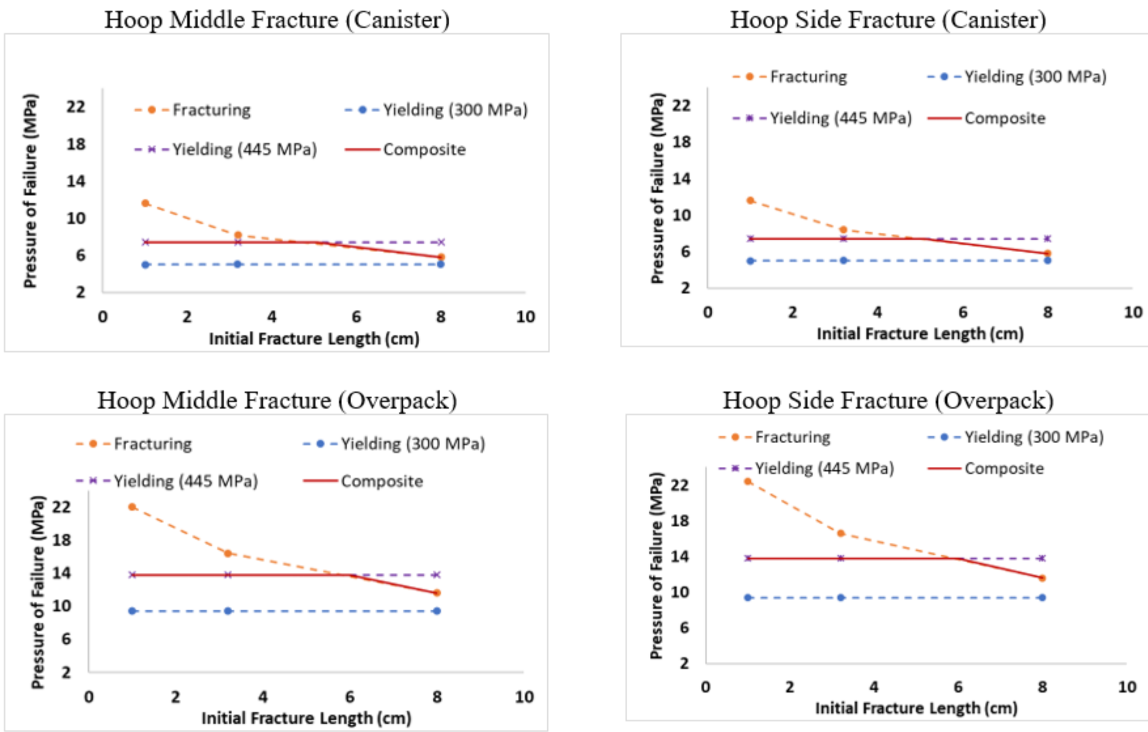

Figure 4. Critical pressure for hoop fractures of different lengths in both the canister and the overpack.

4 CONCLUSIONS

The following observations are made.

- Fracture growth will not happen if the ultimate strength of stainless steel is reached before critical pressure for fracture growth.
- In all cases analyzed in this study, the failure processes (both fracturing and plastic yielding, if perfectly plastic model is assumed) are unstable. Once failure starts, it continues at a constant pressure. Note that these models are quasi-static and with constant pressure. This behavior may change in a transient model.
- For both the canister and overpack, longitudinal initial fractures around 1 cm and longer will grow due to internal pressurization.
- The critical pressures required to fail the overpack are greater than those for the thinner canister.
- In both the canister and overpack, hoop fractures for the assumed initial fracture lengths approximately less than 6 cm will not grow before plastic yielding occurs. For fracture length more than an approximate value of 6 cm, failure is controlled by fracture propagation.

The next steps in modeling WP breach behavior are to account for residual stress in the shell, and internal/external pressure conditions, and to calculate a dynamic pressure-time history by adding a pulse of heat energy to a constrained volume of fluid representing a saturated WP. The model can also include heat dissipation, external dissipation of fluid pressure, and coupling of internal pressure to breach transmissivity. Breaches in both the DPC shell and disposal overpack should be considered in series combinations.

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