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Modeling Internal Degradation and Crushing of Dual-Purpose Canisters – 22284

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ABSTRACT

Dual-purpose canisters (DPCs) are used for storage and transportation of spent nuclear fuel. Such canisters consist of a cylindrical shell of stainless steel and a basket to hold the spent fuel assemblies. Common basket designs include the rectilinear "egg-crate" style and a "tube-and-plate" style. Aluminum is used in many basket designs for neutron absorber plates, or as a metal-matrix composite material from which basket plates are made that jointly serve the functions of neutron absorption, heat dissipation, and basket structure. If DPCs are disposed of directly without modification, the packaging will eventually be breached, exposing the basket and fuel to groundwater. The aluminum will corrode relatively quickly, degrading neutron absorption and increasing reactivity. Other components (basket plates, DPC shell, fuel spacer grids) will also degrade eventually, further changing the configuration.

With degradation of the basket structure, collapse may occur under the weight of the fuel. Collapse of the shell and basket can also occur in response to external loading from groundwater and bentonite buffer swelling pressure prior to breach and flooding of the DPC. To predict the possibility of criticality events in the disposal environment, it is important to understand the evolution of the fuel/basket/canister configuration. This paper presents numerical modeling of basket collapse by simulating: (a) collapse of the fuel and basket under its own weight as a result of degradation caused by corrosion and (b) collapse of the shell and contents due to external hydrostatic loading. The model is developed for a representative generic MPC-32 fuel basket.

Modeling basket collapse due to corrosion degradation is carried out using a 3D distinct-element method. A detailed model simulates all components of the canister with reasonable detail. Fuel rods, guide tubes, spacer grids, end nozzles, basket plates, and the canister are all modeled individually using coarsely discretized rigid blocks with strength and stiffness concentrated at the block contacts. Bending stiffness and strength of fuel rods is also represented correctly to determine possible failure of rods during collapse. The modeling for DPC collapse due to external hydrostatic loading is carried out using the finite volume method. Appropriate constitutive models are used for different materials. The external pressure required to collapse the DPC and the mode of failure are estimated for the DPC loaded with fuel and without fuel, and for two plate joint welding conditions.

INTRODUCTION

Dual-purpose canisters (DPCs) are used for storage and transportation of spent nuclear fuel. Such canisters consist of a cylindrical shell of stainless steel and a basket to hold the spent fuel assemblies. Common basket designs include the rectilinear "egg-crate" style and a "tube-and-plate" style. Aluminum is used in many basket designs for neutron absorber plates, or as a metal-matrix composite material from which basket plates are made that jointly serve the functions of neutron absorption, heat dissipation, and basket structure. If DPCs are disposed of directly without modification, over geological timescales, the packaging will eventually be breached by initial cracks (fractures) due to stress corrosion cracking processes, exposing the basket and fuel to groundwater. Fresh water is also a neutron moderator. The aluminum will corrode relatively quickly, degrading neutron absorption and increasing reactivity. Other components (basket plates, DPC shell, fuel spacer grids) will also degrade eventually, further changing the configuration.

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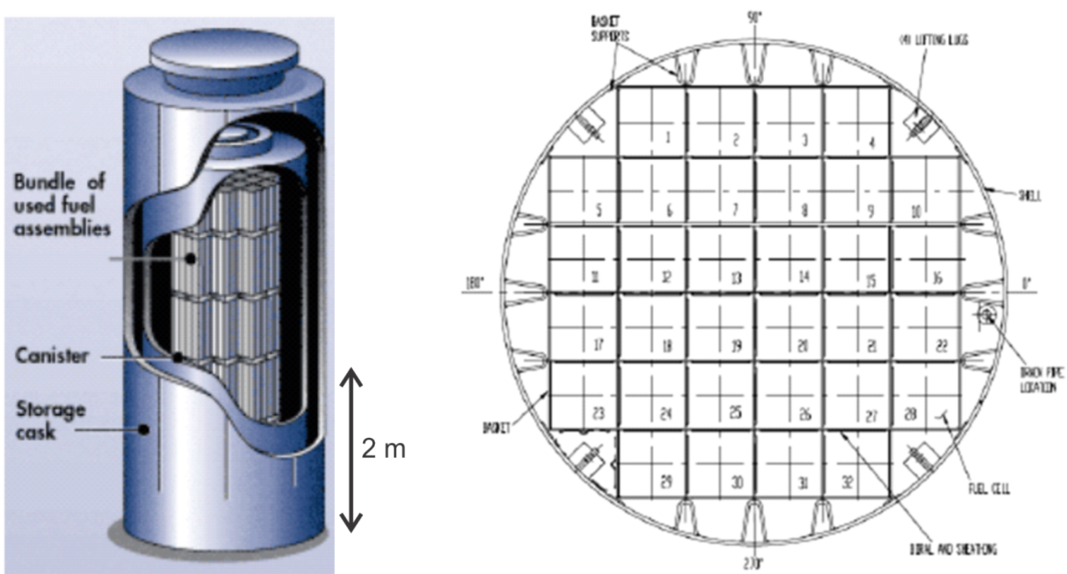
With degradation of the basket structure, collapse may occur under the weight of the fuel. Collapse of the shell and basket can also occur in response to external loading from groundwater and bentonite buffer swelling pressure prior to breach and flooding of the DPC. Reduction in neutron absorption resulting from degradation and increase in reactivity caused by neutron moderation from groundwater and fuel rearrangement from collapse could result in a configuration where a criticality event could occur. To predict the possibility of criticality events in the disposal environment, it is important to understand the evolution of the fuel/basket/canister configuration. This paper presents numerical modeling of basket collapse by simulating: (a) collapse of the fuel and basket under its own weight as a result of degradation caused by corrosion and (b) collapse of the shell and contents due to external hydrostatic loading. The model is developed for a representative generic MPC-32 fuel basket.

CANISTER AND BASKET

Description

The system (illustrated in Fig. 1a) consists of a steel canister (cylindrical shell) inside a thicker overpack (steel). The canister has a rectilinear honeycomb basket (shown in Fig. 1b) in the middle used to hold the spent fuel assemblies. There are two basket configurations: egg-crate and tube-and-plate. Illustrated is the egg-crate configuration.



(a) (b)

Fig. 1 a) Canister with overpack and fuel assemblies; b) Configuration used for this study showing MPC-32 basket in a canister.

Older designs use steel plates with thin plates of Boral® (aluminum-B4C composite) as neutron absorber that are fixed to the longitudinal structural plates by thin cover sheets of stainless steel. For newer designs, the basket structure is made using aluminum-based Metamic-HT, which also serves as the neutron absorber material and prevents the spent fuel from going critical.

The configuration used for this study corresponds to MPC-32 basket (egg-crate) made of Metamic-HT and PWR fuel assembly with 17 × 17 fuel rods in each assembly.

The fuel assembly, shown in Fig. 2, includes the following structural components indicated in the figure:

- End nozzles (304L stainless steel) at the top and bottom,
- Spacer grids (zircaloy),
- Control rod guide tubes (zircaloy), and
- Fuel rods (spent UO_2 pellets inside zircaloy cladding).

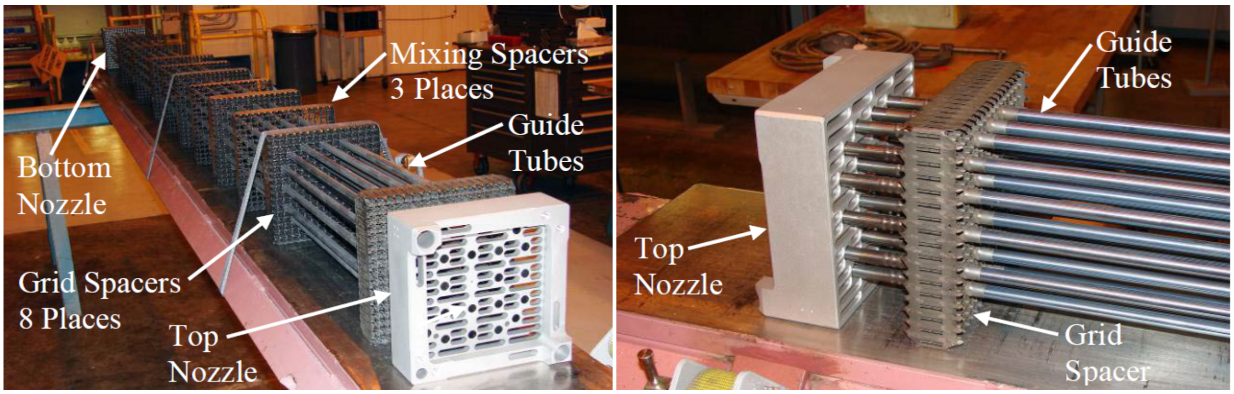


Fig. 2 Fuels assembly and its components (Lindgren and Durbin [1]).

Degradation Sequence of Basket Internals

The order of degradation of the basket internals along with the approximate timeline for different components is shown below. Note that the degradation times are order-of-magnitude approximations used to set the sequence in which different components degrade in the model.

1. Metamic-HT® basket plates (mainly aluminum): mechanical lifetime of 500 years (based on two-sided corrosion, 10 mm thickness, and rate of 10 μm/year).
2. Stainless steel canister: mechanical lifetime 5,000 years (based on two-sided corrosion, 10 mm thickness and 1 μm/year).
3. Zircaloy spacer grid: mechanical lifetime of 500,000 years (based on two-sided corrosion, assumed thickness of 1 mm, and 0.001 μm/year).
4. Zircaloy fuel cladding: mechanical lifetime of 500,000 years (based on one-sided corrosion, assumed intact thickness of 0.5 mm, and 0.001 μm/year).
5. Zircaloy control rod guide tubes: mechanical lifetime of 500,000 years (based on two-sided corrosion, assumed thickness of 1.0 mm, and 0.001 μm/year).

Based on these estimates, it is likely that the aluminum-based basket plates will fail first. The thin-walled canister shell and the internal basket supports will fail long before the spacer grids corrode completely. Accordingly, the overpack is included in the model along with the canister shell, allowing longer duration support that will determine the configuration of fuel assemblies. The overpack is much thicker than the canister shell, and it is assumed that the overpack retains its shape and constrains the canister internals for at least 25,000 years.

BASKET DEGRADATION MODEL

The modeling to simulate degradation due to corrosion is carried out using a Particle Flow Code (*PFC3D)*, a 3D distinct-element method code developed by Itasca [2]. The model simulates all components of the canister with reasonable detail. Fuel rods, guide tubes, spacer grids, end nozzles, basket plates, and the canister are all modeled individually using coarsely discretized rigid blocks.

The deformability and strength of the components are simulated by using soft contacts between these rigid blocks with the strength and stiffness concentrated at the contacts. The numerical model along with its different components is shown in Fig. 3. Bending stiffness and strength of fuel rods is also represented correctly to determine possible failure of rods during collapse as discussed in the next section. Degradation is modeled by weakening the strength of internal contacts for the components. Components are failed but not deleted, so total mass in the model is preserved.

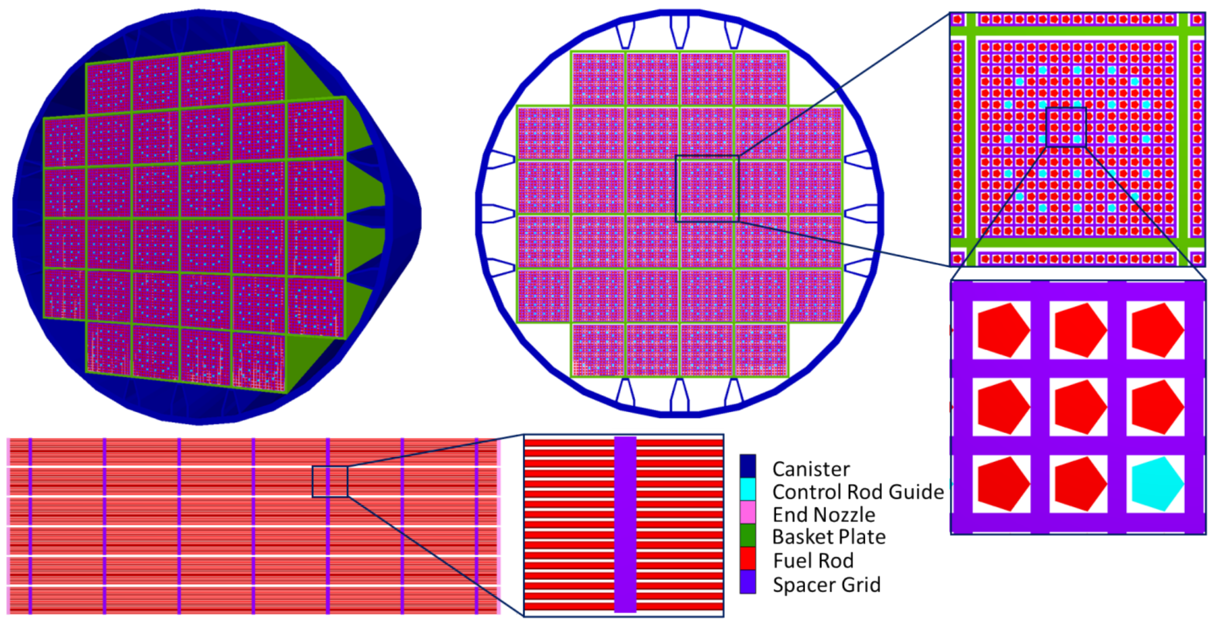


Fig. 3 Model setup showing different components in perspective view (top left), transverse view with zoom-in (right) and longitudinal view with zoom-in (bottom).

Bilinear Model for Fuel Rods

A single rod model was used to calibrate the bending behavior of fuel rods. The contact stiffness is proportional to the modulus of the rod and inversely proportional to the segment size because the segments are rigid and the deformability is concentrated only at the contacts. The fuel rod is loaded in pure flexure by imposing rotation of both ends and the resulting moment-curvature curve is compared with laboratory data from Ahn et al. [3]. The rod behaves as a composite beam with spent fuel inside showing brittle behavior and the surrounding zircaloy casing being ductile. Once the fuel inside cracks, the tensile stresses are carried only by the fuel rod cladding and as a result, the stiffness of moment-curvature curve reduces (point B) as shown in Fig. 4.

A modified contact model (bilinear) was implemented in *PFC3D*. In the bilinear model, once the maximum tensile stress due to bending reaches a certain value (point B), the tangent modulus is reduced to a specified residual value. Unloading at any point uses the unloading modulus (specified as original modulus for this study), resulting in hysteresis. A good match with the lab results was obtained as shown in Fig. 4.

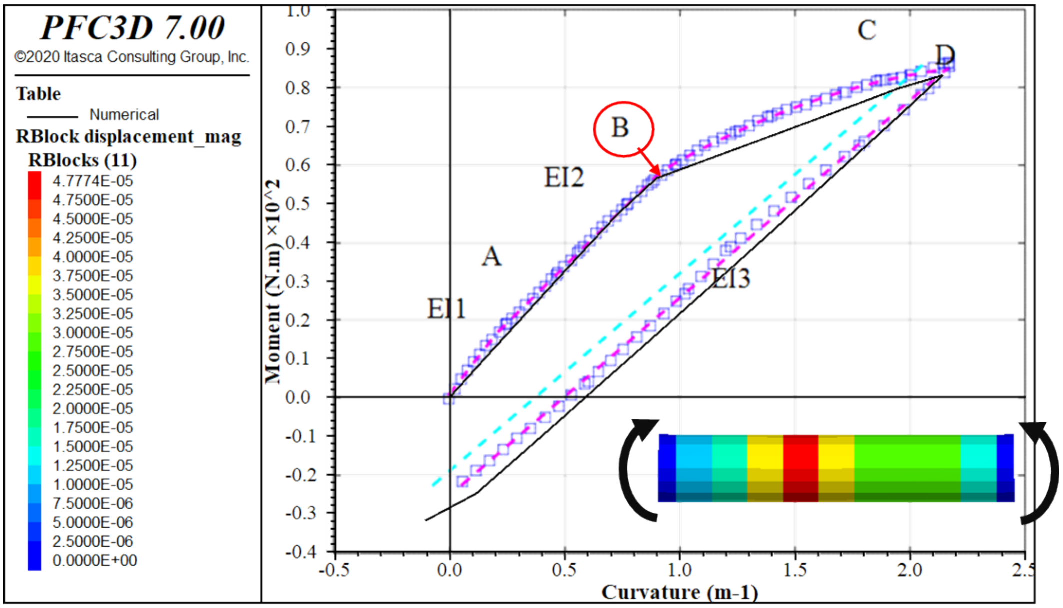


Fig. 4 Representative moment-curvature response of a single fuel rod from laboratory tests by Ahn et al., [3] (pink) superimposed on top of numerical results from the *PFC* bilinear model (black).

Modeling Strategy

The main goal of the basket degradation model is to evaluate general trends of evolution of the internal configuration. Degradation follows a sequence based on corrosion rates of different materials, while also considering randomness. Sensitivity analyses evaluate different scenarios by varying corrosion rates, applying heterogenous corrosion rates, and changing the order in which internal supports in the canister degrade.

Two types of models have been set up that differ in terms of length along the axis of the canister. The first model, referred to as the 2.5D model, simulates the length between the centers of two adjacent spacer grids (about one-seventh of the total model), whereas the second model simulates the entire canister, including the end nozzles. The purpose of the first model is to be able to test different features and scenarios quickly and gain insight into model behavior before running full-length models with longer run times. Fuel rods, guide tubes, spacer grids, end nozzles, basket plates, and the canister are all modeled individually using coarsely discretized blocks for both models. The 3D model, in which the entire length of the canister is modeled, is shown in Fig. 3.

Results of 2.5D Model

The 2.5D model was used to conduct sensitivity analyses with respect to orientation angle of the plates relative to horizontal and vertical (assuming that the canister axis is horizontal). It was assumed that the plates fail first, followed by sequential degradation of supports, canister, and spacer grids. The spacer grids were degraded in stages, starting with grids with largest loads and proceeding with less loaded grids. The results of the 2.5D model are presented for three different orientations in Fig. 5 to Fig. 7. Each figure shows the evolution of basket configuration after certain components have degraded.

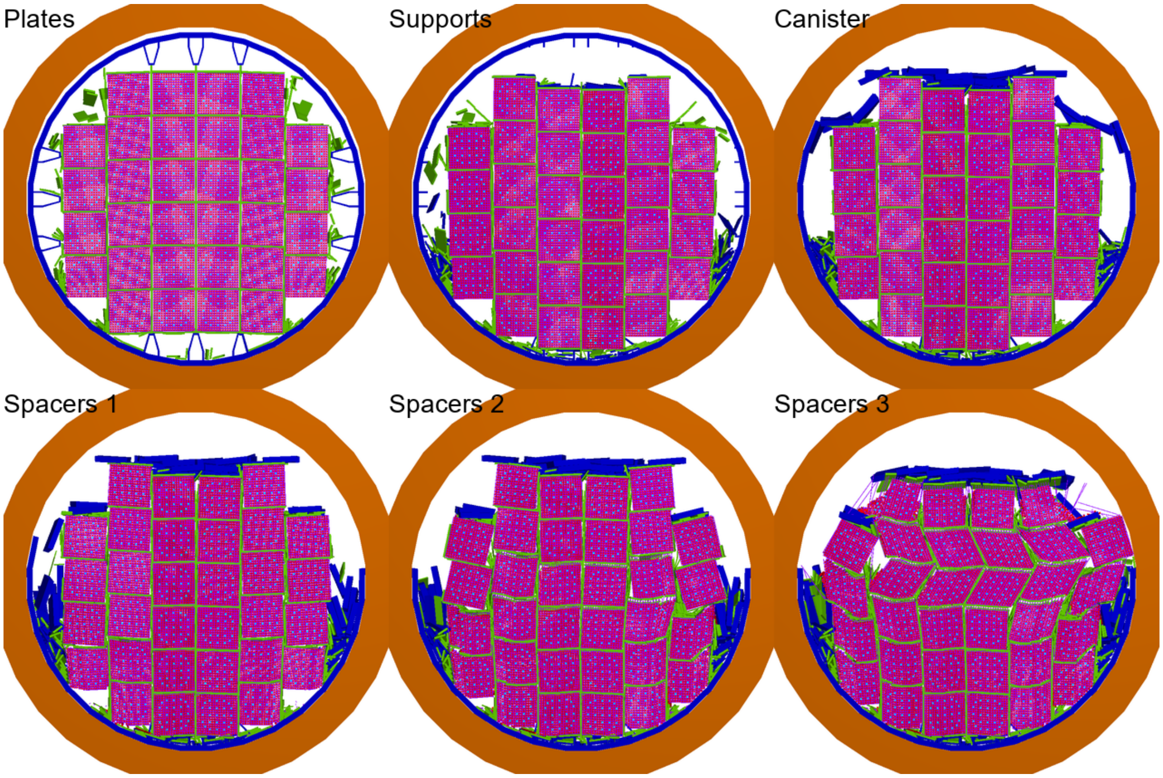


Fig. 5 2.5D model after degradation of plate, supports canister and spacer grids for 0° orientation.

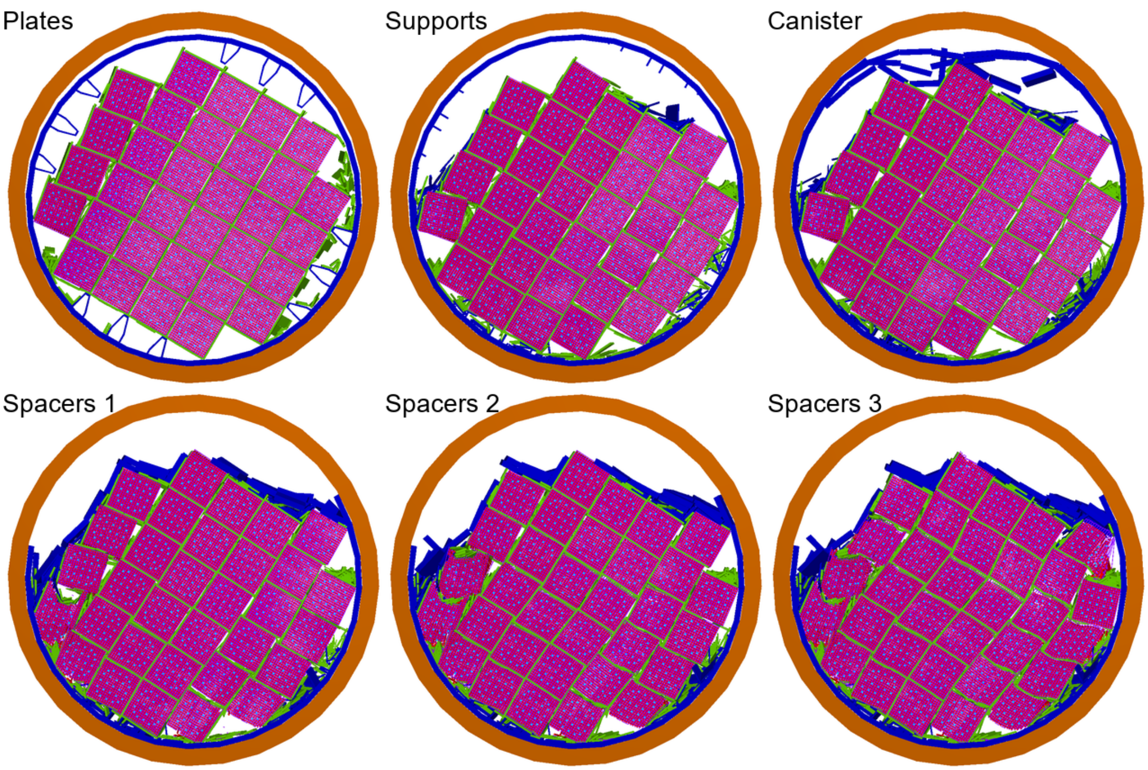


Fig. 6 2.5D model after degradation of plate, supports canister and spacer grids for 30° orientation.

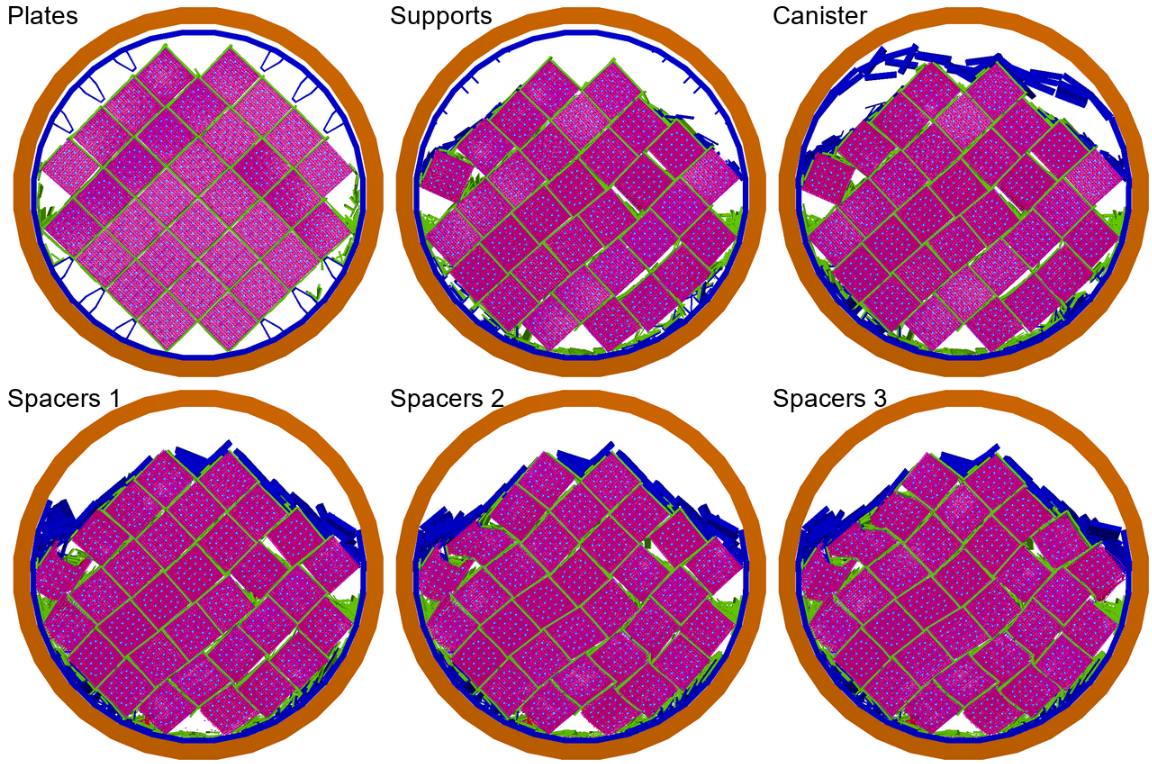


Fig. 7 2.5D model after degradation of plate, supports canister and spacer grids for 45° orientation.

A few important observations can be made from the results of the 2.5D models.

- The degradation of the lower half of the canister does not have a significant impact on the final configuration because the overpack constrains the degraded canister and the overall shape remains more-or-less the same. The upper half of the canister does have some impact due to interaction with degraded plates, but the upper half of the canister is not expected to fail easily due to degradation because it is subject to much smaller loads. The most important components are the internal canister supports, which carry most of the load and have smaller thickness than the canister, and as a result may degrade much faster. For full 3D simulations, only the degradation of the internal supports is modeled instead of the entire canister.
- Weakening of spacer grids in the middle and at the bottom does not lead to any significant configuration change because the confinement prevents the spacer grids from unraveling. The grids at the top do come apart, but again, they are under the least amount of load and may not fail for a much longer duration compared to those at the bottom and the middle. Furthermore, the failure mechanism simulated for spacer grids here is quite extreme with weakening of all contacts as opposed to failure of a few contacts or hinge formation. It can thus be assumed that fuel assemblies will mostly remain intact unless failure occurs in rods due to flexure.

Results of 3D Model

Sensitivity analysis were carried out on 3D models representing an entire loaded DPC to capture effects from the major variables controlling model behavior. Eight models were run to evaluate the variation in response with respect to

(a) heterogeneous rate of degradation (i.e., assuming that the components in the region around the middle of the canister degrade at a faster rate compared to the rest of the canister),
(b) order of degradation of different basket internals (i.e., internal supports degrading before the plates) and,
(c) the angle of the plates relative to horizontal and vertical (0° and 45°).

The results of the 3D model, in which supports are failed before spacers, for two states of degradation and two plate orientations are shown in Fig. 8.

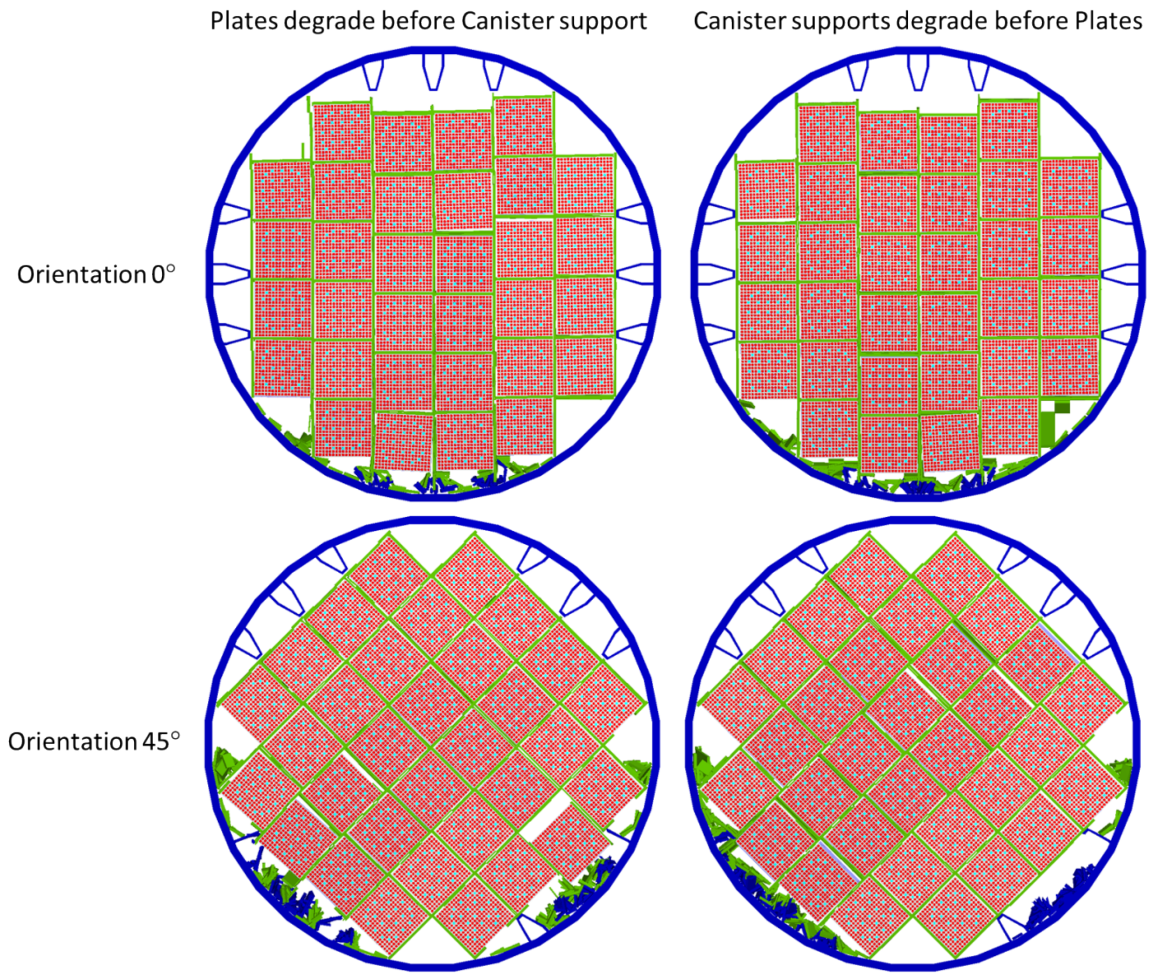


Fig. 8 Final configuration for full canister length simulations with homogenous rate of corrosion along canister length. The results are presented in matrix form where cases with same sequence of component degradation (e.g., basket plates degrade before internal canister supports) are in the same column and cases with same orientation are in the same row.

The case with non-uniform rate of corrosion and 0° orientation results in the most demand in terms of flexure for the fuel rods. However, even for this extreme case, no failure was observed in the fuel rods. In fact, the degraded internal supports do not even collapse for these cases because the load is transferred to the intact portion of the supports by the bending of fuel rods. Assuming the supports were to collapse, and the rods were bent all the way to the bottom of the canister, the maximum curvature in the fuel rods for this case can be estimated using Euler's beam theory as $2y/x^2$, where y is the maximum vertical deflection (0.16 m) and x is the minimum distance between spacer grids (≈0.6 m).

This gives a maximum curvature of around (0.88 m^{-1}) which is right around the softening point where the fuel pellets inside the rods stop contributing to bending resistance, but the rods are well within the elastic limit. The results along with this simplified analysis are presented in Fig. 9.

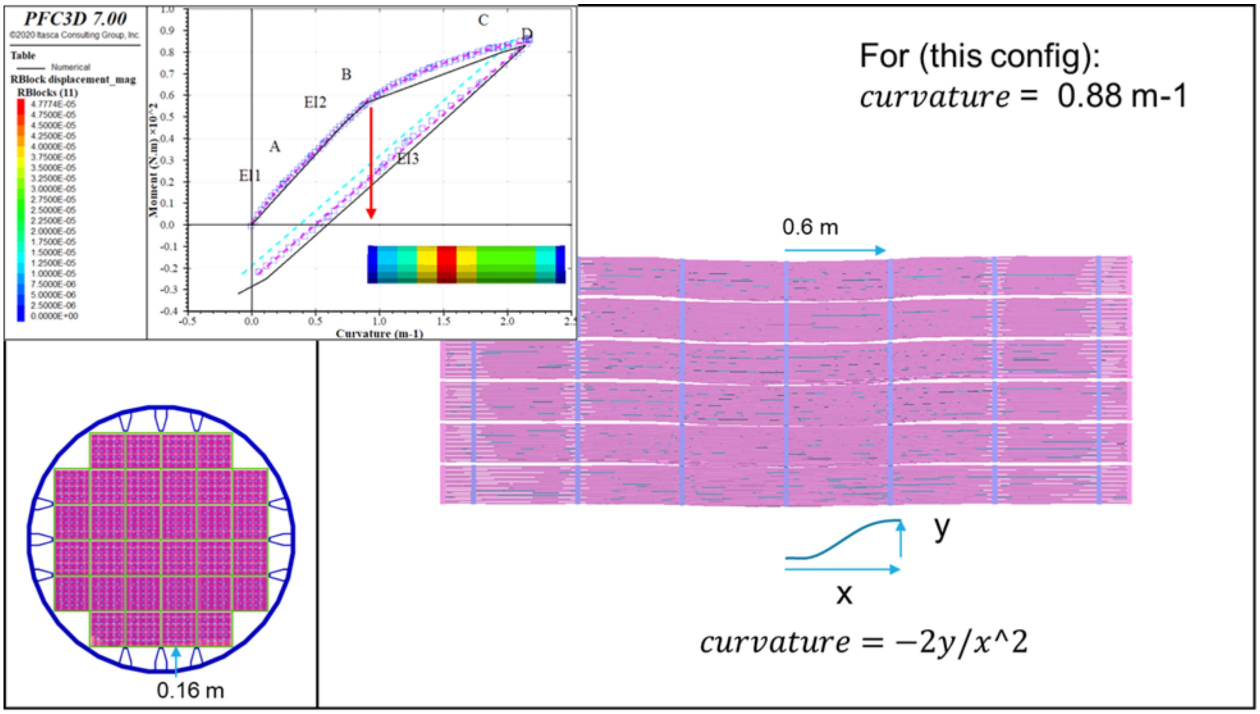


Fig. 9 Simplified calculations showing maximum expected curvature for fuel rods.

CANISTER CRUSH MODEL

Collapse of the shell and basket can occur in response to external loading from groundwater and bentonite buffer swelling pressure prior to breach and flooding of the DPC. There are several potential mechanisms that can lead to structure failure of the DPC and its basket due to the external pressure exerted on the DPC shell. These mechanisms include:

- plastic failure of the basket or the DPC components as a result of bending, shearing, or a combination of the two mechanisms;
- buckling of the structural components; and
- failure of welded joints.

The finite volume method code, *FLAC3D* [4] is used to analyze this problem with explicit representation of the canister structure and its internals, basket and fuel assemblies accounting for the interaction of all components. While there is a limitation that full nonlinear behavior of structural components is not included, load levels at which ultimate strengths of aluminum or stainless-steel components are reached, if reached, are noted. The DPC is assumed to be constrained by a thicker, breached overpack structure. The approach is based on an assumption that collapse of the overpack is not plausible under expected repository conditions, including loading from groundwater pressure, from buffer/backfill swelling and drift closure deformation.

Model Description

The *FLAC3D* model assumes symmetries along the canister axis, representing a section from the middle of the spacer grid to the half-distance of two spacer grids (Fig. 10). Consequently, the model does not account for the effect of the lids on the stiffness and strength of the DPC. It is reasonable to assume that the effect of the lids in a section in the middle of the DPC will be relatively small. The DPC is located inside the cylindrical overpack, which in this analysis is assumed to be rigid. The maximum gap between the DPC and the overpack is assumed to be 2 cm. The external load is applied as the hydrostatic pressure on the outside surface of the canister shell.

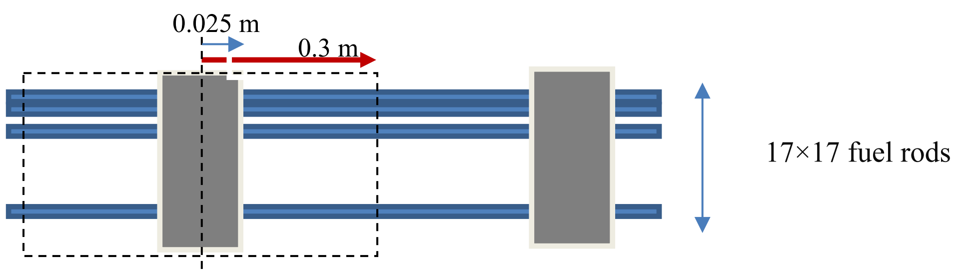


Fig. 10 *FLAC3D* model representation along the canister axis. The black dotted box shows the extent of fuel assembly and spacer grid included in the model. Only half spacing between spacer grids (shown by red arrow) is represented in the *FLAC3D* model.

It is assumed that the dominant failure mode of the DPC is controlled by buckling of the canister shell and the basket plates. The structural behavior is thus assumed elastic, but maximum stress is monitored and noted if it exceeds the ultimate levels in aluminum or stainless-steel components.

Two configurations, an unloaded basket (without fuel) and a fully loaded basket (with fuel), are considered. In reality, the horizontal and vertical plates are slotted together such that in a given section, one (either vertical or horizontal) plate is continuous while the other is cut (i.e., plate sections on two sides of the joint can rotate independently). The illustration of the joint between the plates is shown on the left in Fig. 11. Each plate is 50% continuous and 50% cut. The joints are then welded. In the model, the joints between the vertical and horizontal basket plates are in one case considered fully welded and they are fully joined, and in another, partially welded. In the latter case, translational degrees of freedom of the nodes along the joint are linked together, but rotations are not (two plots on right in Fig. 11).

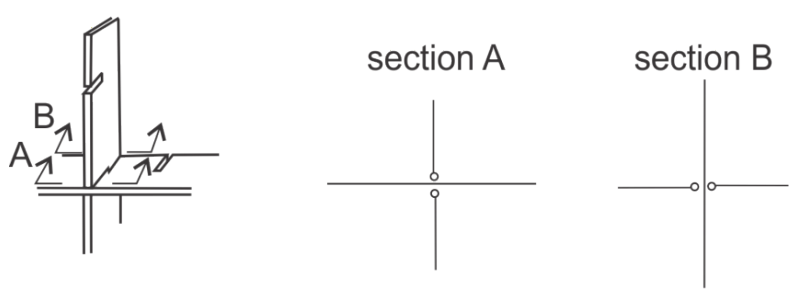


Fig. 11 Illustration of the joints between the plates and their representation as partially welded.

The geometry of the DPC crush model in the cross-section is shown in Fig. 12. The canister shell, support elements and the plates are modeled as shell structural elements. The shell elements used to represent the plates have interfaces on both sides that allow interaction between the plates and the fuel assembly. The fuel assembly is represented using solid zones with the properties and geometry varying between sections that represent assembly of the fuel rods and the spacer grids.

In each case, the model is first equilibrated to gravitational loading, and in the following steps, increasing hydrostatic pressure is applied in increments along the outer surface of the DPC. The system is equilibrated for each loading increment.

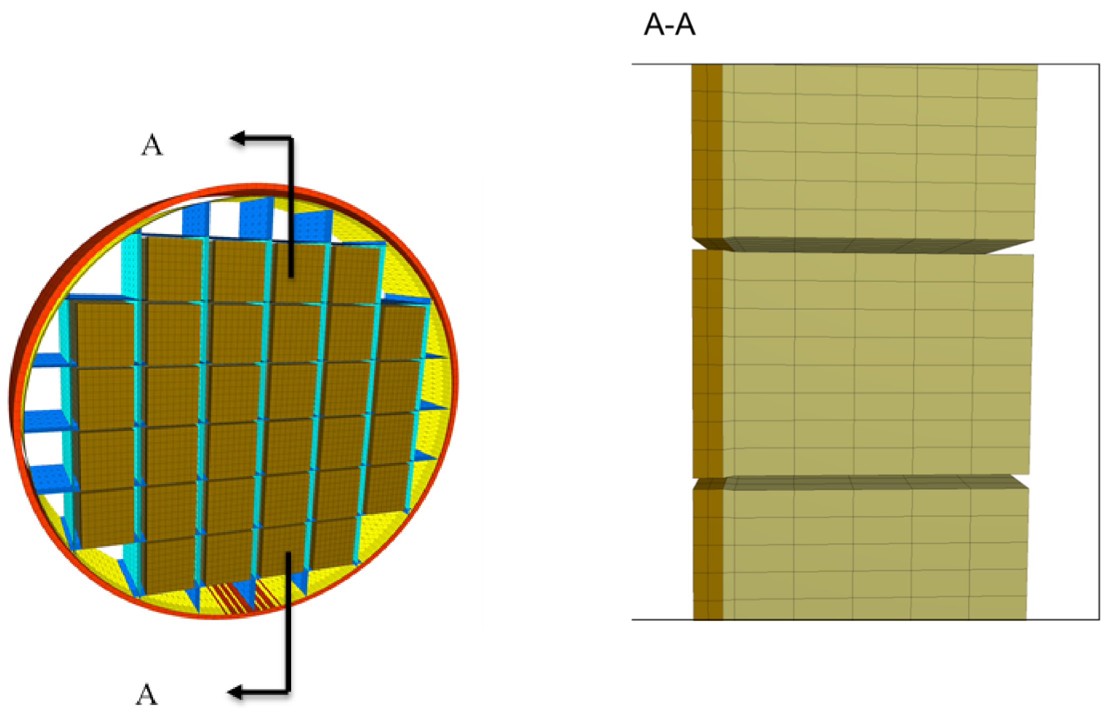


Fig. 12 Analyzed model with structural elements representing DPC and basket structure, and solid zones representing fuel rods, spacer grids, and overpack.

Results

In Fig. 13, displacement magnitude contours are compared for 15 MPa external hydrostatic pressure for the partially and fully welded joints. For the fully welded joints, both with and without fuel, the states shown are stable, and these are final displacement magnitudes, whereas for the partially welded joints, the state is unstable, and the displacements are not final. Deformation is dominated by the DPC shell deformation and is larger for the partially welded basket joints and the basket without fuel. In terms of the ultimate stress, the results are similar for the partially and fully welded cases.

The results of the analyses show that in the case of fully welded joints, yielding of the DPC happens first, and it is reached for the external hydrostatic pressure level of 7 MPa. Yielding of the basket plates is reached for loading levels greater than 15 MPa and buckling occurs at levels larger than 20 MPa. Reduction of the overall structure stiffness due to weaker jointing between the basket's vertical and horizontal plates affects the levels of ultimate loading, causing the DPC to yield at hydrostatic pressure of 6 MPa basket plates to yield at loading levels above 10 MPa, and buckling at levels above 10 MPa. Even though yielding (at the extreme fiber) happens at a relatively low level of external loading, the deformation capacity of the structure and load-bearing capacity are large.

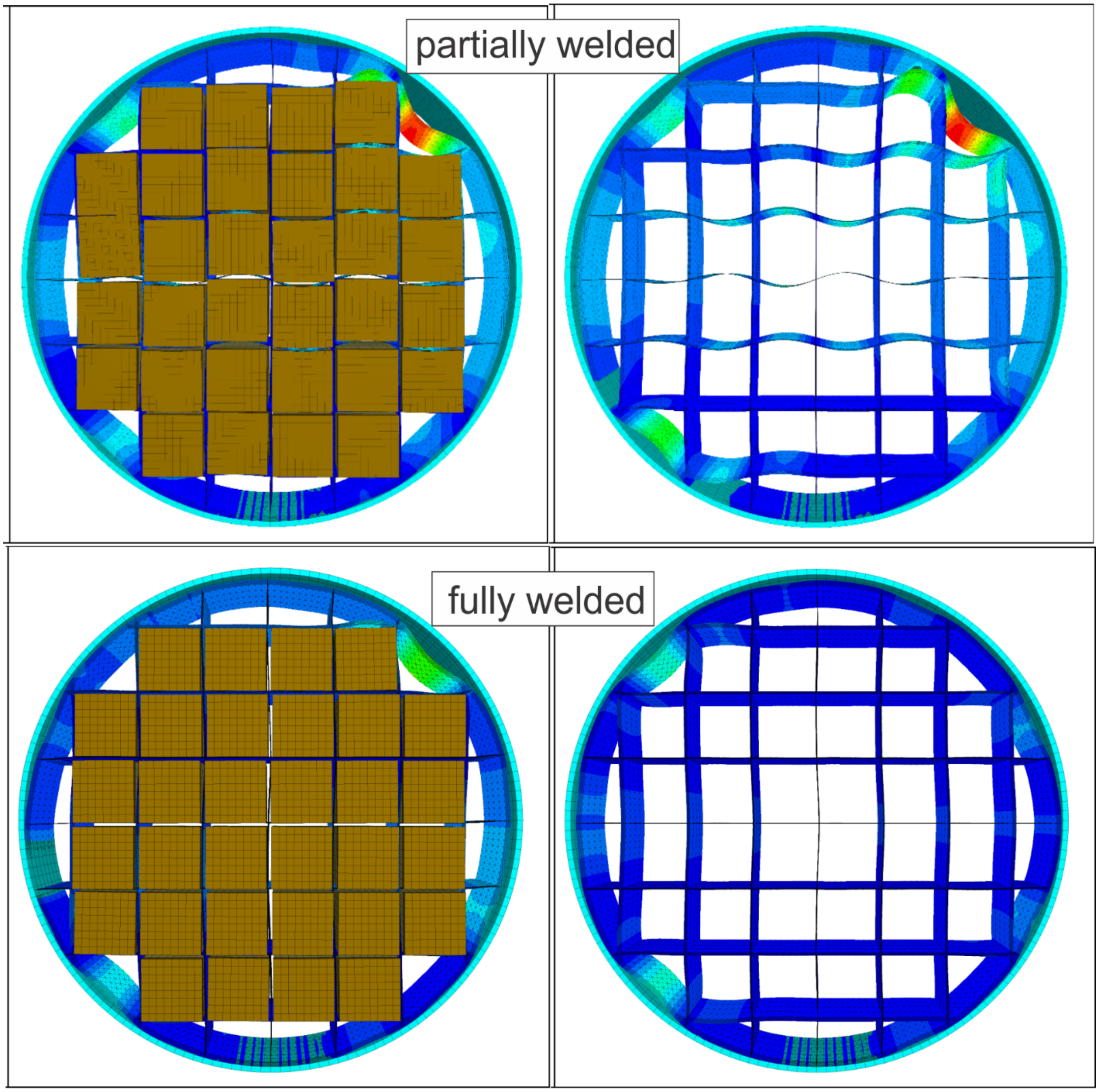


Fig. 13 Displacement magnitude contours for the partially welded basket joints (top) and fully welded basket joints (bottom) loaded with fuel (left) and without fuel (right) caused by external pressure of 15 MPa. Contour values vary between 8.5 cm (red) and 0 cm (blue).

CONCLUSIONS

Sensitivity analyses of the basket collapse as a result of degradation of the structural components were carried out using 2.5D models to study the effect of canister orientation including the effect of the overpack. The degradation of the lower half of the canister was not found to have a significant impact on the final configuration because the overpack constrains the degraded canister and the overall shape remains more or less the same. The degradation of internal canister supports was determined to have the most effect. Weakening of spacer grids in the middle and at the bottom also did not lead to any significant configuration change because the confinement prevents the spacer grids from unraveling.

Eight 3D models representing an entire loaded DPC were run to carry out a series of sensitivity analyses to capture effects from the major variables controlling model behavior including relative corrosion rates of basket plates and support braces, canister orientation, and spatial heterogeneity of corrosive weakening of these components. Even for the extreme cases, no failure is observed in the fuel rods.

The collapse of the DPC-basket structure under increasing external hydrostatic load is analyzed for configurations where it is loaded with fuel or empty and where basket joints are fully or partially welded. Although yielding of DPC and basket plates happens at lower pressures, the analysis indicates that the collapse of the DPC and the basket due to buckling of the plates will occur at external loads greater than 10 MPa and 15 MPa, for partially and fully welded joints, respectively.

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