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Modeling degradation of Dual-Purpose Canisters using *3DEC*

Varun[1], A. Riahi[1], B. Damjanac[1] & E. Hardin[2]
[1] *Itasca Consulting Group, Inc., Minneapolis, MN, USA*
[2] *Sandia National Laboratories, Albuquerque, NM, USA*

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1 INTRODUCTION

This paper analyzes the degradation of spent nuclear fuel canisters used for storage and transportation, when those canisters include a fuel basket made mostly of aluminum, if they were to be used for disposal as well. Such canisters consist of a cylindrical shell of stainless steel, and many canister designs use a simple rectilinear “egg-crate” style basket to hold the spent fuel assemblies. Aluminum is used in many basket designs as part of a metal-matrix composite material that absorbs thermal neutrons for reactivity control, helps dissipate radiogenic heat, and forms the basket structure. If the canister is used for disposal, and it is breached after it has been in a geologic repository for thousands of years, and subsequently flooded by ground water, the aluminum-based basket plate material can degrade. With degradation of the basket structure, collapse may occur under the weight of the fuel assemblies. This paper presents numerical modeling of basket collapse, simulating degradation of the basket as a result of corrosion. The model is developed for a representative egg-crate style fuel basket containing 32 pressurized water reactor fuel assemblies.

2 DESIGN AND ANALYSIS

Itasca’s *3DEC* (Itasca, 2016) software is used to simulate the collapse of the fuel basket. The model is set up using different modules for each component so that the level of detail for any component can be changed without affecting the rest of the model. The three modules are for fuel assemblies (arrays of fuel rods with associated hardware), basket plates, and the canister shell. Two types of models have been set up, with the difference being the level of detail to which the components have been modeled.

A detailed model simulates all components of the canister with reasonable detail. Fuel rods, guide tubes, spacer grids, end nozzles, basket plates, and canister are all modeled individually using coarsely discretized blocks. The 3D model is set up as shown in Figure 1 where the entire length of the canister is modeled. To reduce computation time, a representative length equal to the spacing between two consecutive spacer grids can also be modeled if the spacer grids are not expected to deteriorate (results presented here are for the entire canister). Otherwise, modeling the entire length is required. Due to the level of detail (i.e., explicit representation of each rod), this model is suitable to be used as a validation model for static analysis (run time up to 10 days on a typical desktop PC), but the run times for seismic analyses are prohibitive (months).

The fuel assemblies consist of fuel rods, control rod guide tubes, spacer grids, and end nozzles, all of which are simulated as separate bodies. The fuel rods are modeled as long, thin cylindrical blocks. The circular cross-section is approximated as a regular polygon with a user-specified number of sides. A larger number of segments results in better approximation but more computational effort. Between 8 and 12 segments allow for sufficient detail while keeping run times reasonable. The deformability and flexural strength of rods is modeled by discretizing each rod into a certain number of segments along the length of the rod. Each segment is rigid, but the contacts between segments have stiffness and strength. The stiffness and tensile strength are calibrated to match the analytical response or composite bending behavior observed in laboratory tests as shown in Figure 1. Again, a higher number of segments provides higher resolution but also at an increased computational cost. Around 5 segments between adjacent spacer grids provide enough resolution. Some of the positions in the array of fuel rods are occupied by guide tubes, and the center position by the instrumentation tube. These tubes are modeled the same way as fuel rods but matching their stiffness and strength properties to represent hollow tubes.

The structure of actual spacer grids is very detailed, including thin plates, dimples and springs to hold the fuel rods. Representation of all details would be computationally prohibitive. Instead, the spacer grid is modeled as a rectilinear array of plates. The thickness of plates modeled is larger than the actual thickness such that the boundary condition that the rods have no free room available to move in direction normal to their axis is simulated correctly. However, the density of the plates is reduced accordingly to match the mass of the spacer grid. The end nozzles are massive blocks of stainless steel on both ends of the fuel assembly. They are also modeled as a rectangular array of plates with thickness such that the rods cannot move normal to their axis.

There are two main types of baskets: egg-crate and tube-and-plate. The egg-crate design is the focus of this study. It consists of parallel, longitudinal plates that extend the full length of the basket. They are indexed together to form a rectilinear array. Each square cell in the array accommodates one fuel assembly. In the model, aluminum-based metal-matrix composite plates are assumed and are modeled using rigid blocks joined at the contacts where actual plates are welded together. If needed, the plates can be discretized along both the length and width to simulate deformability and strength. The plates can also be discretized by multiple blocks along the thickness, and some discretization blocks can be deleted progressively to model the reduction in strength and stiffness due to corrosion. The canister is currently modeled as a hollow cylinder with a certain thickness. The side supports inside the cylinder are also modeled. The location and details of the side supports are crucial because they have a significant influence on how the fuel assemblies stack up if the basket structure degrades and fails. For the current model, the support elements are assumed to be continuous along the length of the canister.

A simplified model (justified by the detailed model) is used for static parametric studies and for dynamic analyses. In this model, each fuel assembly is represented as a single set of coarsely discretized blocks along the length with equivalent density, modulus, and strength. In other words, an equivalent continuum is used to represent the assembly of rods.

Reducing the detail in modeling the fuel assemblies greatly speeds up the computation and allows seismic analyses to be run in one to two days. This is a good assumption if the individual rods in the assemblies do not break. In case the rods do break, a hybrid approach can be used to model the fuel assembly of interest in more detail while using the simplified approach for the rest of the assemblies. This allows for correct modeling of the interaction between the assemblies and study of the response of a particular assembly without imposing significant computational overhead. Different models can then be run to study the behavior of assemblies at different locations.

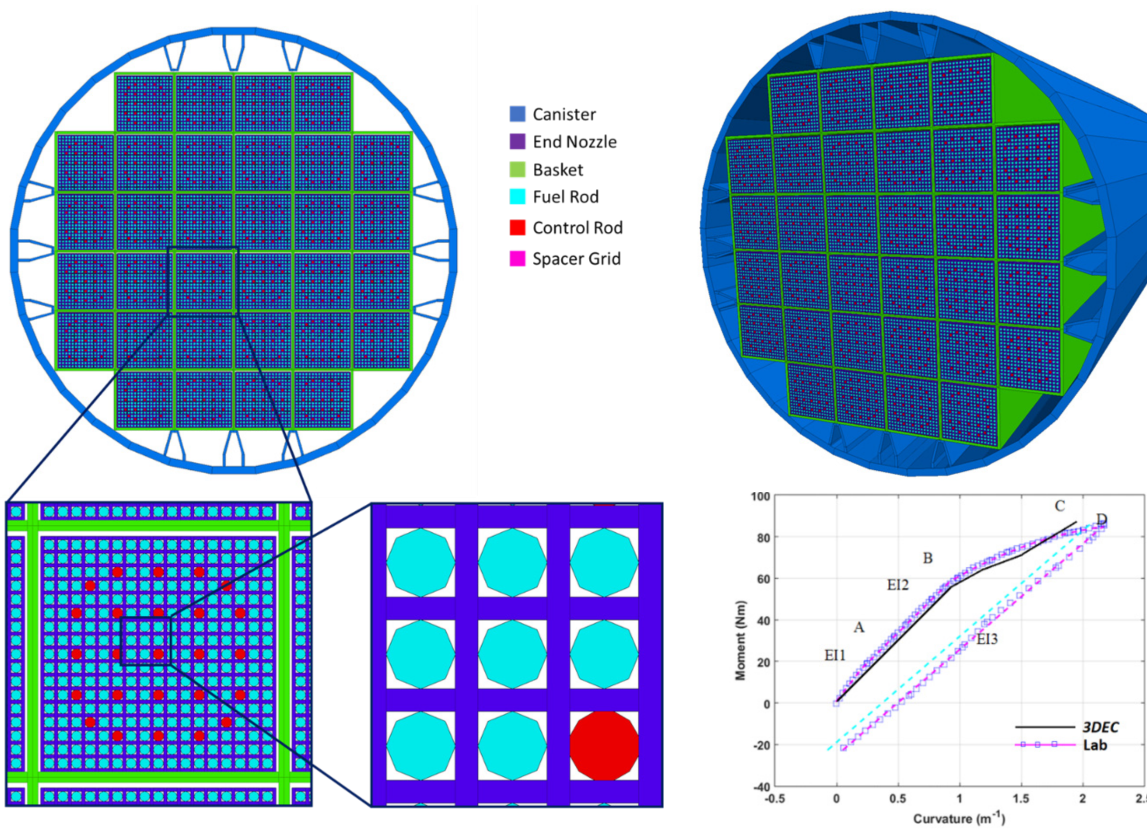

Figure 1. Model setup showing different components in transverse view (left), in perspective view (top right) and moment-curvature response of a single fuel rod obtained from *3DEC* model compared with laboratory data from Ahn et al. 2018 (bottom right).

3 RESULTS AND DISCUSSION

Both the detailed and the simplified models were run in three stages to model the basket collapse due to degradation of structural components caused by corrosion.

- Stage 1: The first stage is to establish initial equilibrium under gravity.
- Stage 2: It is assumed that the basket plate structure has corroded away, represented in the model by deleting the basket plates, so that the fuel assemblies stack up on top of each other. The final configuration is closely controlled by the configuration of internal supports in the canister. The basket structure can also be degraded progressively by breaking connections between basket plates.
- Stage 3: The spacer grids are assumed to corrode away next. The end nozzles, control rod guide tubes, and fuel rods are still intact (although they may be deformed). The final configurations in Stage 3 for the detailed and the simplified models are shown in Figure 2. The detailed model is still not in complete equilibrium with the leftmost and rightmost assemblies at the bottom still moving very slowly towards the center. However, the assemblies are no longer falling, and the subsequent minor adjustments are unlikely to damage to fuel rods. The final configurations from both models are comparable.

After Stage 3 of the static analysis, a seismic analysis is carried out using the simplified model. It is assumed that the canister is embedded in the ground at least partially so that ground motion is transferred directly to the canister. To model the seismic shaking, all three components of a strong ground motion history are applied as velocities of the canister in three directions. The snapshots of the configuration at four different instants of time are shown in Figure 3. The results indicate that there is some bending and possible twisting of the fuel assemblies during the shaking. The assemblies showing the most bending can be investigated in detail using a hybrid model.

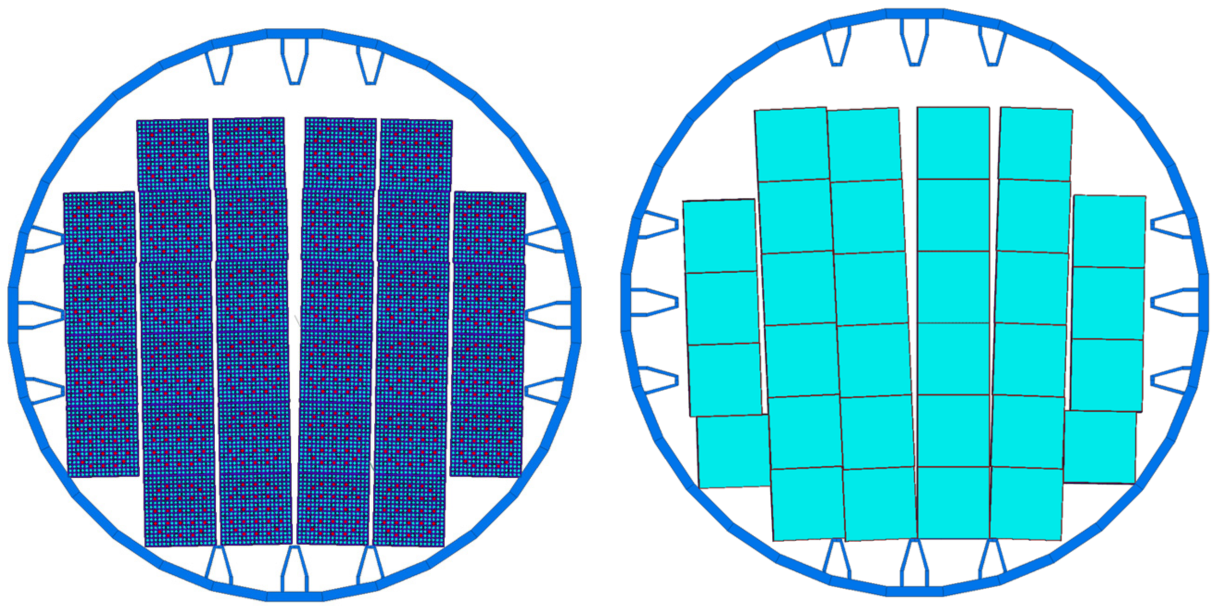

Figure 2. Final configuration at the end of Stage 3 for the detailed model (left) and simplified model (right).

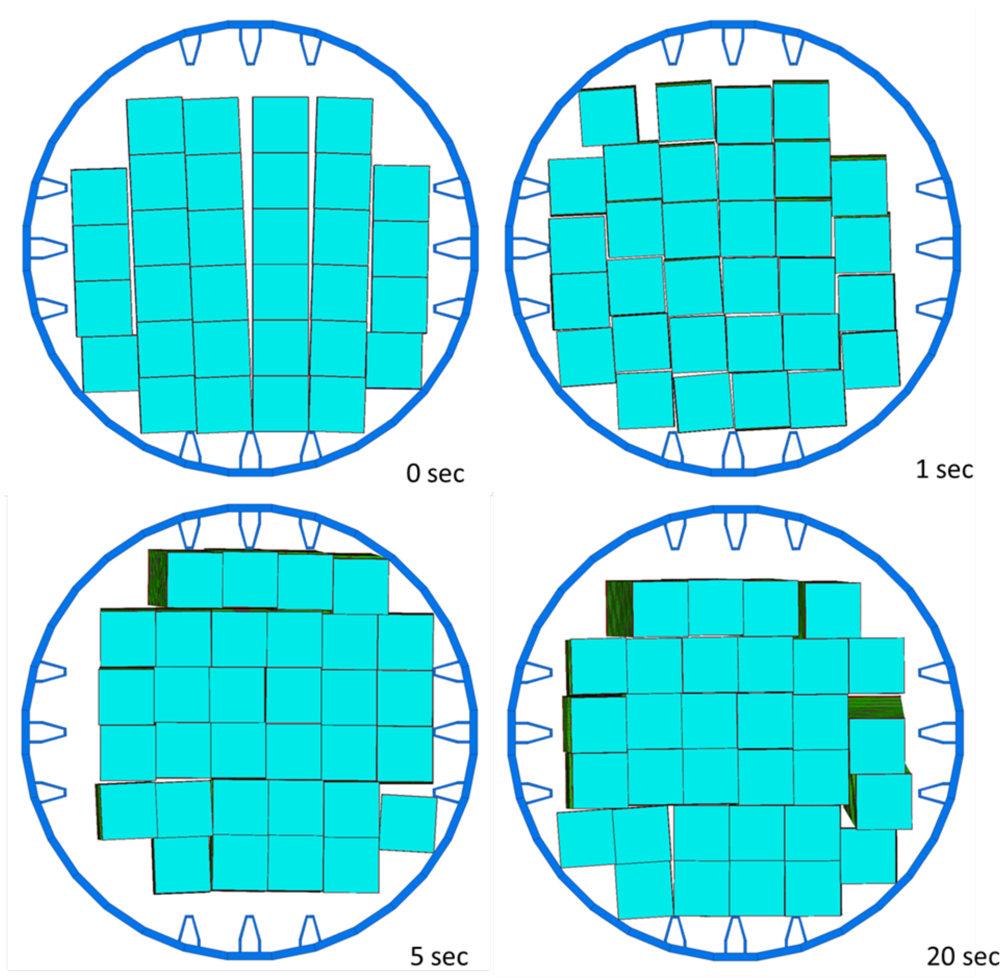

Figure 3. Model configuration at different times during the shaking.

4 CONCLUSIONS

The models of basket collapse using *3DEC* software are developed and used for initial simulations of the collapse of a typical 32-assembly fuel basket due to degradation of the structural components caused by corrosion. In order to optimize the run times, two models were created. The detailed model explicitly represents all important basket components including the plate structure, and the various components of the fuel assemblies. In this model, although the detail of the cross-section of the fuel rods (with fuel pellets inside zircaloy cladding) is not explicitly represented, the fuel rod model matches the experimentally obtained moment-curvature curve of the fuel rods. Simulation of the basket collapse (by removing corroded structural elements like plates and spacer grids) shows that none of the rods fail. Consequently, it was justified to create the simplified model in which the fuel assembly was represented using an equivalent continuum model. The simplified model allowed faster run times for the simulation of complete basket collapse as a result of complete degradation of the plates and the spacer grid, as well as simulation of the effect of seismic shaking of the Dual Purpose Canister (DPC) with the internal structure in the collapsed state.

REFERENCES

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