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Thermal Modelling of Advanced Test Reactor Fuel in a Generalized Dry Storage System

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Changing the World's Energy Future

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Interoffice Memorandum

Idaho National Laboratory

Date: December 2, 2022

To: E. F. Eidelpes, Used Fuel Management

From: M. J. Murphy-Sweet, Intern

Subject: Thermal Modeling of Advanced Test Reactor Fuel in a Generalized Dry Storage System

Summary

Star-CCM+, a computational fluid dynamics (CFD) software was used to conduct modeling and simulation of the thermal performance of a dry storage configuration consisting of Department of Energy Standardized Canisters (DOESCs) loaded with aluminum-clad spent nuclear fuel (ASNF.) The configuration includes nine DOESCs loaded with Advanced Test Reactor ASNF contained within a stainless steel overcanister centered in a ventilated, concrete overpack. The simulations were used to estimate the maximum temperatures reached by backfill gases inside the overcanister and DOESCs.

Background

The Department of Energy (DOE) currently manages over 400 different types of spent nuclear fuel (SNF.) One such fuel is the ATR ASNF. The ATR is a pressurized water reactor designed to test fuels and materials in a high neutron environment. The utilized aluminum-uranium alloy fuel is a series of curved plates designed to fit in the ATR core's cloverleaf-shaped pattern.

After in-reactor irradiation in the ATR, the irradiated nuclear fuel is cooled for a period of time in the ATR canal. Upon reaching a satisfactory level of decay heat, the ASNF can be dried and placed into dry storage systems where they can continue to cool. This move to dry storage currently includes loading ATR ASNF into vented dry storage canisters located within Idaho National Laboratory's Chemical Processing Plant (CPP)-603 building located at the Idaho Nuclear Technical and Engineering Center. However, to support DOE's current road-ready dry storage initiative, the option of loading ATR ASNF into sealed, standardized canisters (i.e., the DOE SC) is being evaluated. The loaded DOESCs would be stored within concrete overpacks outside of CPP-603 and would allow for decay heat removal through natural convection with the environment.

Aluminum-clad nuclear fuel has a potential to corrode and produce corrosion products termed oxyhydroxides that retain moisture in the from of physiosorbed or chemisorbed water. Thus, the main concern regarding of dry storage is the potential for radiological gas generation, which could create flammable atmosphere internal to the canisters or lead to canister

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overpressurization. A robust dry storage configuration backfilled with inert helium gas could prevent oxygen ingress and eliminate this flammability concern. To address overpressurization, pressure computations are being performed. While simulations of radiolytic gas generation require high-fidelity, multi-physics modeling and simulation work that accounts for, among other things, the availability of corrosion products, the radiation levels involved, and the complex interactions of individual chemical species within a canister, the CFD software package, STAR CCM+ offers a reliable way to model the fluid flow and heat transfer of the dry storage system by solving transport equations for finite volumes. This affords a cost-efficient way to estimate temperatures within ASNF dry storage configurations, which are a pressure controlling parameters.

For performing thermal analysis, a quarter cut of the considered ATR dry storage configuration was modelled and simulated in STAR-CCM+ version 2206 by utilizing turbulence and radiation models to accurately capture the fluid flow and heat transfer phenomena being investigated. Results are shown for the maximum temperatures reached by the dry storage system under ambient conditions described in US Nuclear Regulatory Commission Regulation CR-7260 (NUREG/CR-7260) once they have reached steady state [1] [2].

Approach

Model

The evaluated dry storage system is modeled as a cylindrical, concrete overpack that is 215 in tall with four rectangular openings located at the bottom end and near the top end which are 24 in by 6 in. These openings are arranged in a cross-like pattern. They serve as vent ports and connect the overpack environment to a 77 in diameter internal cylindrical overpack cavity. This cavity is lined with a 2 in stainless-steel liner, and holds stainless-steel over canister. This over canister has spots for nine 15-ft-long DOESCs with an outer diameter of 18 in, arranged in a wagon wheel pattern featuring one internal canister and eight external ones. The over canister is sealed and backfilled with argon gas, whereas the DOESC with helium gas.

Each DOESC is loaded with three levels of 4 stainless-steel ATR buckets (i.e. fuel baskets designed to carry four individual ATR ASNF elements) arranged in a circular pattern. Circular stainless-steel spacer plates are placed between each level of buckets to support the distribution of heat from the buckets and to limit movement of the overcanisters' internal components. A sectional view of the modeled dry storage system is shown in Figure 1 [3]

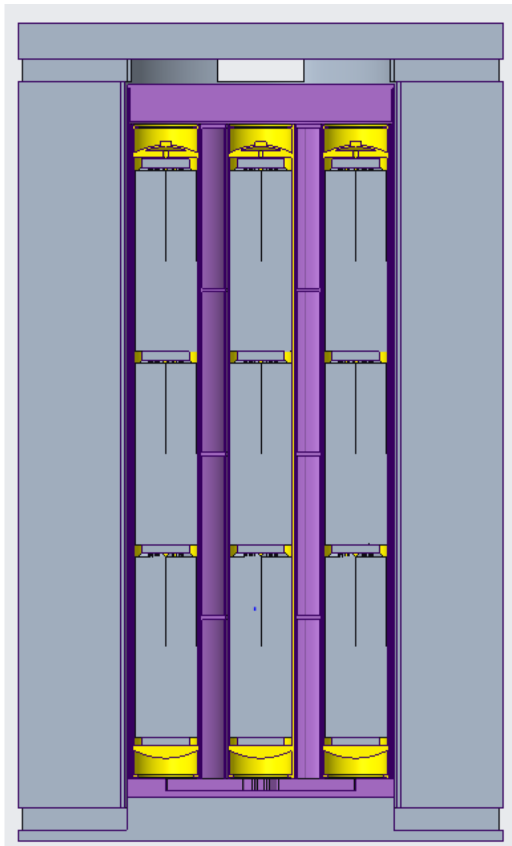

Figure 1: Assembled Dry Storage System

Actual ATR fuel elements consist of 19 layers of aluminum plates held together by aluminum equipment. The gap between plates is .078 in, and the fuel elements are 49.5 in long. However, for the sake of simplicity and to limit the required CFD meshing efforts, the individual fuel plates were solidified and then modeled as solid elements as the internal gaps are very difficult to imprint in light of the larger geometries being modelled. This simplification introduced a safety factor, as it decreased the elements' overall surface area, thus decreasing their ability to dissipate heat to the backfilled air as well as decreasing the volume of the backfill helium in the canister which both cause increases in temperature of the backfill helium. A comparison between the actual ATR fuel element geometry and that of the model is shown in Figure 2, which displays a cross-sectional vies of the DOESC quarter.

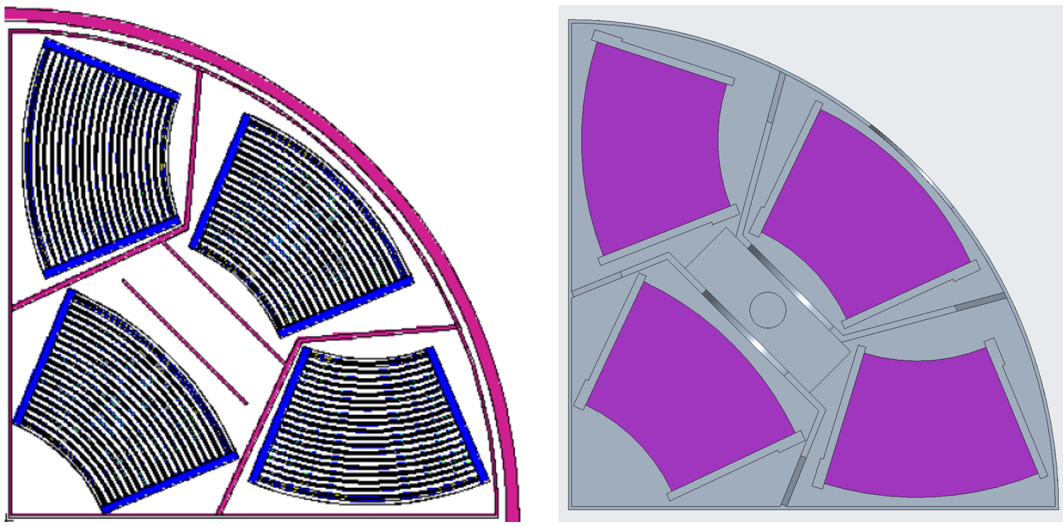

Figure 2: Differences in Fuel Geometry

The geometry was modeled in CREO and then brought into the Star-CCM+ geometry software extension. In the modeler, regions were created for the internal gas regions. Initially, the entire overcanister was modeled, but eventually the model was cut and a symmetric quarter model was used to reduce the computational costs. The cut planes were defined by points along the longitudinal overpack center line and the center of the overpack vent ports. The geometry was then processed through the imprinting operator built into the modeler, causing the software to match the tessellations on the mating faces of the regions.

Next, the model was brought back into Star-CCM+, and the regions were assigned according to their physical states, then broken down into materials and location. The model was then run through the built-in mesher. A base size of 1.5 in was chosen for the polyhedral mesher. Polyhedral cells were chosen because of their superior performance in terms of heat transfer and energy resolution. In addition to the main volume mesher, the thin and prism layer mesher were also chosen. The thin mesher creates additional cells in volumes whose regions are thin in comparison to their surroundings, which comes in handy for the canister walls and baskets. The prism layer mesher enables cells to be generated to solve for the viscous sublayer along walls. Both the thin and the prism layer meshers were set to have two layers. When the model had run through all the meshers the cell count totaled over 25 million cells.

Boundary Conditions

Each ASNF element was set to produce 30 W of heat. This value was chosen based on data provided by INL's DOE SNF database it represents the maximum heat output of ATR ASNF when being pulled from wet storage in the ATR canal. This heat generation should bound the maximum temperature reached by the DOESC's internal atmosphere, though it is worth noting that the average decay heat generation from the ATR elements within the DOE SNF database is significantly lower (i.e. 15 W) [4].

The faces of the cells that are along the cut planes made from reducing the model size are given a boundary condition set as a symmetry plane. The symmetry plane boundary condition mirrors the energy and flow leaving the cell face and applies the same amount back. The outer walls of the concrete cask were given a thermal boundary condition of convective heat transfer with a heat transfer coefficient of 5 W/m^2-K and an ambient temperature of 38^oC. All regions had the radiation temperature set to 38^oC. The surface emissivity for each region is given in Table 1. The bottom vent ports' outer faces were set to a stagnation inlet and the top vent port outer faces were set as pressure outlets. Both had the pressure set to atmospheric pressure and had a stagnation temperature of 38^oC.

Region	Emissivity
Concrete	.7
Stainless Steel	.9
Fuel	.8
Aluminum	.8

Table 1: Surface Emissivity of Material in Model

Simulations were run with varying radiation and turbulence models to provide a matrix of values. The first simulation, run with a laminar assumption and no radiation, provided temperature and flow results that justified the use of the models. The turbulence models investigated were the k-omega turbulence model and the two-layer realizable k-epsilon model which was run with a shear-driven flow model and a buoyancy-driven flow model. On average, the addition of this model reduced the temperature by of around 15%.

The radiation models employed were the discrete ordinates (DO) and surface to surface (S2S) model. Both simulations showed agreement in terms of their results, and reduced temperatures by around 55%. Values for the results can be found in the Appendix attached to this memo.

Results

The S2S model and two-layer realizable k-epsilon model with the buoyancy driven flow model are the most accurate models for simulating the transport equations. This claim is based on the following observations: with little difference between the S2S and DO radiation models, the S2S results are likely to be more accurate as a result of the S2S model needing less time to reach steady state. The turbulence model employed was chosen because of its reputation of performance in near-wall regions and its adaptable y+ wall treatment. Which is of great benefit considering the relatively thin fluid regions that are driven vertically along the walls of the liner, overcanister and DOESCs.

Region	Maximum Temperature (C)
Argon	170.1

Center Helium	198.1
Outer Helium	174.5
Fuel	198.1
Canister	171.1
Over Canister	159.7

Table 2: Results from the Final Simulation

The maximum temperature reached by the backfill helium, which is the region of interest for the gas generation phenomena was 198.1°C, representing a 160°C increase over the environmental temperatures specified. Additional maximum temperatures are given in Table 2. Figure 3 is a through cut of the dry storage system which shows the temperature profile in the model. It can be observed that the hottest temperatures occur towards the top and center, whereas the coldest temperatures are towards the bottom and the outer edges.

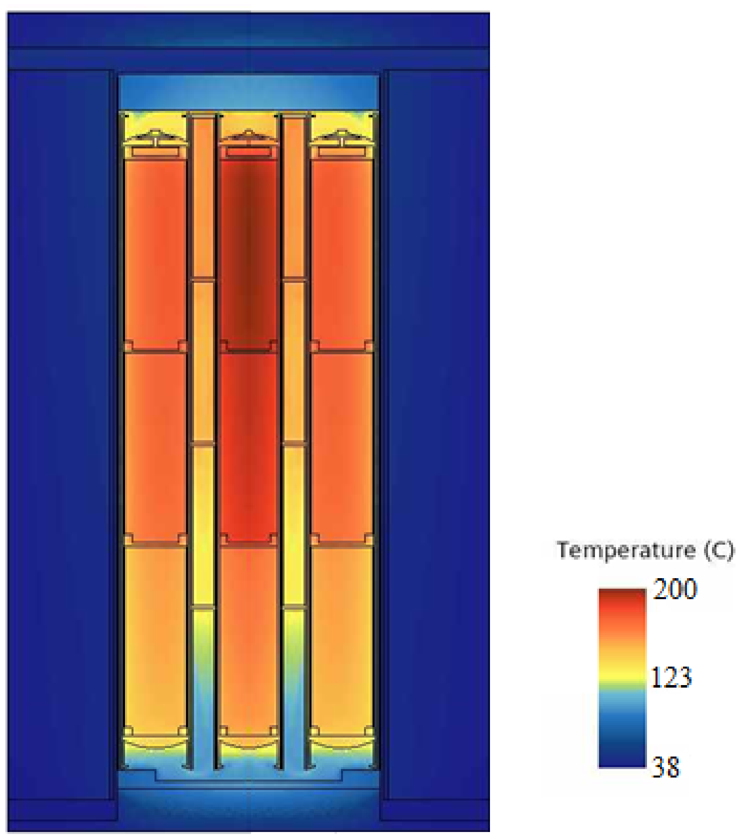

Figure 3: Temperature Distribution in a Through Cut of the Dry Storage System

Conclusion

Based on the results, it is recommended that elements that have higher amounts of decay heat be placed towards the bottom and in the outer DOESCs, while keeping the elements that have lower amounts of decay heat be placed towards the top and in the center DOESC. This would yield a better temperature distribution and lower the temperature reached by the fuel and thus by the backfilled helium resulting in lower pressure.

Future Activities

In pursuing further thermal analyses of the ATR ASNF loading in the dry storage system, it is recommended that the accident conditions that are outlined by NUREG 7260, a simulation or experiment in which the model is run to steady state and a fully engulfing flame is introduced. Regulations would indicate that the ambient and radiation temperatures of the environment should be increased to 800^{o}C, then examined for 30 minutes in a transient simulation. The temperature increases of the fuel elements and canisters would indicate the maximum temperature reached in a given accident scenario and would increase confidence in the dry storage systems' overall thermal performance.

Another recommendation would be to investigate situations that would compromise the dry storage system's ability to dissipate heat. An example would be to run a simulation in which the inlet and outlet of the dry storage system were blocked as though by debris. This situation would force the heat that is normally dissipated from the overcanister wall to be dissipated through the outer concrete walls.

Additionally, experiments could be performed on a scaled model, with dummy fuel elements that featuring heat-generating foils. Thermocouples could be used to take temperature samples throughout the model using. The temperature results could then be compared to a CFD model that has been modified in accordance with the scale model, enabling validation of the results presented in this paper.

References

[1] STAR-CCM+ v10.02, User Guide, CD-Adapco, 2018.

[2] K.Hall, G. Zigh, and J. Solis. CFD Validation of Vertical Dry Cask Storage System (NUREG/CR-7260) US Nuclear Regulatory Commission. May 2019.

[3] Idaho Cleanup Project Core, Criticality Safety Evaluation for Storage of ATR Fuel in BU-GSF-ATR4 Buckets at the IFSF, Idaho Cleanup Project Core. U.S. Department of Energy. June 2018.

[4] The Department of Energy Spent Fuel Database (SFD), Version 8.1.8, March 31, 2022.

Appendix

I. Turbulence Simulation Results

Temperature (C)	**Laminar**	**Real K-ε (Shear)**	**Real K-ε (Buoyancy)**	**K-ω**
Argon	453.3	382.5	327.7	406.8
Center Helium	557.7	488.0	435.3	510.8
Outer Helium	509.5	431.1	380.7	458.7
Fuel	557.7	488.1	435.3	510.9
Canister	456.6	385.2	331.2	409.6
Over Canister	399.2	325.6	286.2	354.33
% Difference		-15%	-25%	-10%

II. Radiation Model Simulation Results

Temperature (C)	**Base Model No Radiation**	**Surface to Surface (S2S)**	**Discrete Ordinates (DO)**
Argon	453.3	183.3	183.2
Center Helium	557.7	209.6	210.0
Outer Helium	509.5	184.1	188.6
Fuel	557.7	209.6	210.0
Canister	456.6	184.1	184.1
Over Canister	399.2	173.0	172.8
% Difference		-60%	-60%

III. Radiation and Turbulence Models Comparisons

Temperature (C)	**Base Model No Radiation**	**S2S & Shear Driven**	**S2S & Buoyancy Driven**
Argon	453.3	170.1	170.1
Center Helium	557.7	198.1	198.1
Outer Helium	509.5	173.5	174.5
Fuel	557.7	198.1	198.1
Canister	456.6	171.1	171.1
Over Canister	399.2	159.7	159.7

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