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Thermal Modeling of Advanced Test Reactor Fuel in a Generalized Dry Storage System Under Hypothetical Accident Conditions

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Interoffice Memorandum

Idaho National Laboratory

Date: July 18, 2023

To: E. F. Eidelpes, Used Fuel Management Department

From: M. J. Murphy-Sweet, Used Fuel Management Department

Subject: Thermal Modeling of Advanced Test Reactor Fuel in a Generalized Dry Storage System Under Hypothetical Accident Conditions

Summary

Work was performed to investigate the thermal behavior of a sealed aluminum-clad spent nuclear fuel (ASNF) dry storage configuration under hypothetical accident conditions during long-term storage. The considered system consists of a concrete dry storage overpack; a welded over canister, backfilled with argon; and nine Department of Energy (DOE) standardized canisters (DOESCs) loaded with ASNF, backfilled with helium gas. One technical concern associated with the long-term storage of ASNF includes radiolytic hydrogen generation. The yield of large quantities of hydrogen could lead to DOESC over pressurization or a flammable internal atmosphere. While flammability concerns can be resolved by preventing the ingress of oxygen, the canister pressure is partially controlled by the atmosphere temperature. This memorandum summarizes the results of modeling and simulation (M&S) work completed with Star CCM+ (a computational fluid dynamics [CFD] software) considering the thermal effects of a fully engulfing flame and another scenario with the vent ports of the concrete dry storage overpack completely blocked. The goal was to determine the bounding maximum temperature of the DOESC internal atmosphere to evaluate a worst-case pressure scenario, as well as the critical vent port blockage durations.

Background

ASNF makes up a sizeable portion of the unpackaged spent nuclear fuel (SNF) that the DOE currently manages at the Idaho National Laboratory (INL). A primary source of this ASNF is INL's Advanced Test Reactor (ATR), which is a pressurized-water reactor designed to test fuels and materials in a high-neutron environment. With the continued operation of the ATR, the amount of ASNF in need of storage continues to grow. After being removed from the reactor, the ASNF cools to a desirable decay heat inside the ATR canal. The fuel is then dried and placed

into vented dry storage systems at INL's Chemical Processing Plant (CPP)-603 building located at the Idaho Nuclear Technical and Engineering Center (INTEC).
To support DOE's current road-ready dry storage initiative, the option of loading ATR ASNF into road-ready, sealed DOESCs is being evaluated. DOESC's containing ATR ASNF could be placed into concrete overpacks allowing for the removal of decay heat through natural convection with the outside environment. However, ASNF tends to corrode and produce aluminum oxide layers on the cladding surface. The physiosorbed and chemisorbed water within these layers is difficult to remove when conditioning the ASNF for dry storage, enabling hydrogen generation associated with a radiolytic breakdown of residual water during extended dry storage [1]. Radiological hydrogen generation could impact ASNF dry storage safety because it could create a flammable atmosphere within the DOESC or it could lead to over pressurization of the sealed canister due to an increased amount of chemical species available in the gaseous phase. The flammability concerns can be addressed by preventing the ingress of oxygen through a robust DOESC design. However, DOESC over pressurization concerns need to be addressed through extensive evaluations. For instance, simulating radiolytic gas generation demands for high-fidelity, multi-physics M&S efforts accounting for a range of variables, such as the availability of corrosion products, the radiation levels involved, and the complex interactions of individual chemical species within a canister. As part of a DOE Office of Environmental Management (EM)-funded program, CFD M&S work has been done to investigate the temperature variations within INL's CPP-603 vented dry storage configurations for 50 years. The results of this work were coupled with a complex chemical modeling framework to compute the resulting concentrations of various chemical species, including molecular hydrogen. Further, the DOESC canister pressure was computed under consideration of the evaluated temperature and species concentrations [2].

Another, simpler approach is to use conservative assumptions such as the radiolytic gas breakdown of all residual water within a canister. For instance, recently completed bounding ATR ASNF dry storage configuration pressure estimations indicate a base case DOESC pressure well below the structural integrity limit [3]. These evaluations assumed a gas temperature of 220°C, expected for normal conditions of storage for the considered configuration [4]. However, associated sensitivity studies indicate a potential for DOESC over pressurization when exceeding a gas temperature of 316°C. Note that this temperature is below the maximum primary service temperature for a DOESC of 343°C [5]. These findings indicate that it is important to develop a profound understanding of the thermal conditions within the envisioned ASNF dry storage systems to allow for conclusions on safety.

Within this report, Star-CCM+ version 2206 [6] is used to simulate the thermal behavior of an ASNF dry storage configuration under a hypothetical fire scenario (according to the conditions laid out in the U.S. Nuclear Regulatory Commission Regulation CR-7260 [7]). The considered system consists of a concrete dry storage overpack, a welded over canister backfilled with argon and nine DOESCs loaded with ATR ASNF backfilled with helium gas. The provided results include the steady-state temperatures of the dry storage system in an environment with an ambient temperature of 38°C, the temperatures within the dry storage system after 30 minutes of being exposed to 800°C ambient temperature, and the helium and argon temperatures after the ambient temperature has returned to 38°C. Another scenario of interest is the thermal response of the configuration if the vent ports of the overpack were completely blocked with debris. Obstruction to the vent ports changes the dominant means of heat rejection (i.e., from natural convection through the air flow under normal conditions to conduction through the concrete overpack). Results of such a scenario are provided as well, including temperatures time histories to allow for conclusions on critical vent port blockage durations.

Dry Storage Configuration Model

Geometry

The evaluated dry storage system is modeled as a cylindrical, concrete overpack that is 215 in. tall with an outer diameter of 133.5 in. that is 29 in. thick with four rectangular (24 in. x 6 in.) openings located at the bottom end and near the top end for eight vents in total. These openings are arranged in a cross-like pattern. They serve as vent ports and connect the environment to the 203 in. tall and 77 in. diameter internal cylindrical overpack cavity. This design is based upon commercially available overpack options and is only representative until an official overpack is chosen. This cavity is lined with a 2 in. stainless-steel liner and holds a 196 in. tall and 73.25 in. diameter stainless-steel over canister. This over canister is loaded with 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 DOESCs are backfilled with helium gas. A sectional view of the modeled dry storage system is shown in Figure 1.

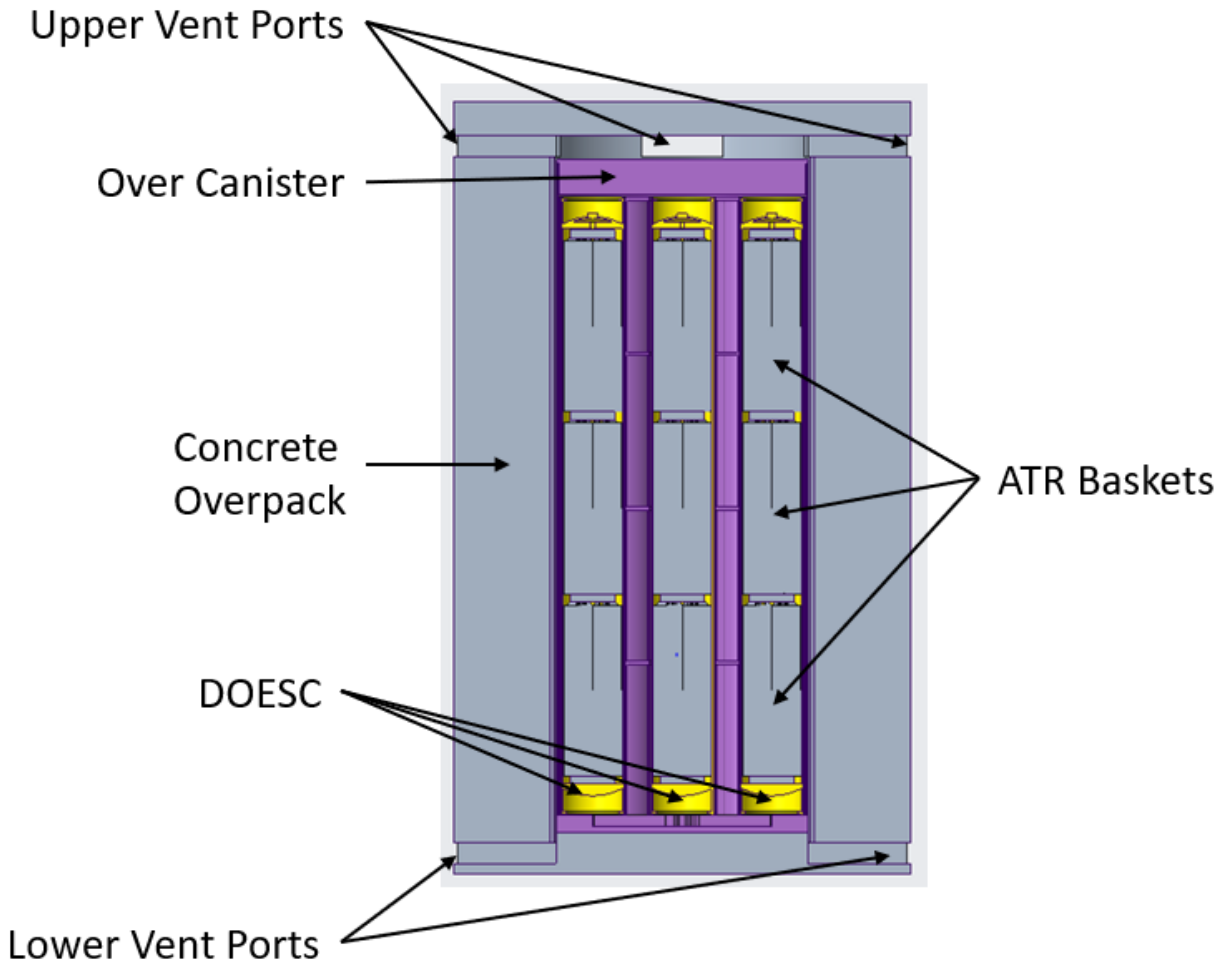
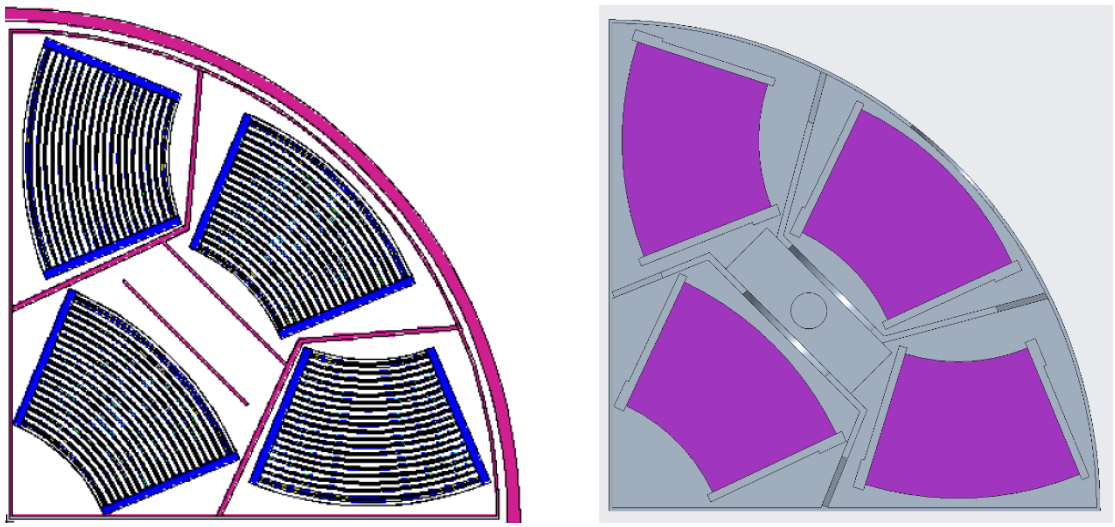


Figure 1. Assembled Dry Storage System.

Each DOESC is loaded with three vertical levels of ATR-4 buckets [8] (i.e., fuel baskets designed to carry four individual ATR ASNF elements) made of borated stainless-steel. Each vertical level consists of four ATR-4 buckets arranged in a circular pattern. Thus, each DOESC is loaded with 48 ASNF elements, and each over canister holds 432 elements. Circular stainless-steel spacer disks are placed between each vertical level of the buckets to limit movement of the over canisters' internal components.

ATR elements are 66.31 in. long, but when the handling tools of the ATR element are cropped off for storage, the active fuel length is 49.5 in. The fuel element consists of 19 layers of aluminum fuel plates held together by aluminum equipment. The fuel plates are curved and are 2.55 in. thick. The first plate and last plate are 0.063 and 0.1 in. thick, respectively. Every other plate is 0.05 in. thick with a water gap in between each plate of 0.078 in. 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 considering the larger geometries being modeled. This simplification introduced conservatism, as it decreased the elements' overall surface area, which in turn increases the heat flux leaving the surface of the fuel element as well as decreasing the volume of the backfill helium in the canister; both events cause increases in temperature of the backfill helium. Figure 2 displays a cross-sectional comparison between the actual ATR fuel element geometry (Figure 2 [a]) and the simplified geometry used in the model (Figure 2 [b]). Only one quarter of the actual DOESC cross section is displayed.



(a) Actual Geometry (b) Simplification.

Figure 2. Geometric Defeature of the ATR Fuel Elements.

The geometry was modeled in CREO [9] and then imported into the Star-CCM+ platform [6]. Initially, the entire over canister was modeled, but eventually the model was simplified, 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. Next, 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. 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 mesher was also used. The thin mesher, which is used in regions like the basket and thin air gaps, creates additional cells in volumes whose regions are thin in comparison to their surroundings.

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 and represents the current maximum heat output of ATR ASNF when being pulled from wet storage in the ATR canal, 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) [10]. The total heat output per DOESC (i.e., 48 ATR ASNF elements) is 1,440 W. The total heat output per over canister (i.e., 432 ATR ASNF elements) is 12,960 W. This heat generation should bound the maximum temperature reached by the dry storage configuration.

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. To create a base steady state scenario for the accident scenarios, a simulation was run to steady state using an ambient and radiation temperature of 38°C.

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°C.

Table 1. Surface Emissivity of Material in Model.

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

Fully Engulfing Flames Model Changes

Initiated from the steady state results found when the ambient temperature was 38°C, the ambient and radiation temperatures are increased to 800°C for 30 minutes of simulation time to mimic the effects of a fully engulfing flame as suggested by NUREG 7260. Once the 30-minute

mark was reached, temperatures were recorded, and the ambient and radiation temperature was brought back down to 38°C, and the simulation was allowed to run until temperatures of the internal regions began decreasing.

For time-stepping in the implicit unsteady model, an initial time step of 0.001 seconds was used, which continued to be increased by a factor of 10 every 10 completed time steps until the step time was 1 second. The heat transfer and temperature of helium and over canister components in the system were monitored and reported every iteration, and after 15 iterations that resulted in a difference of less than 0.0005 between the maximum and minimum of these parameters, the time step was allowed to progress.

Blocked Vent Ports Model Changes

Like the fully engulfing flames, the blocked vent ports simulation is initiated from the steady state results found when the ambient temperature is 38°C, and the time model is switched from steady to implicit unsteady. The time-step is increased and progressed similar to what was previously stated but is allowed to increase to a maximum time step of 60 seconds. To imitate the effect of the vent ports being blocked, the bottom and top vent ports are changed to an adiabatic wall from a mass flow inlet and pressure outlet, respectively. Setting the vent ports to an adiabatic wall will prevent any heat rejection or flow through the boundary.

Results

Mesh Sensitivity

Three base sizes for the polyhedral cells were used to investigate the grid sensitivity of the helium temperatures in the model. Table 2 shows the base sizing specified in the mesh generation along with the maximum temperature reached by the helium regions. Based upon the results from the grid analysis, a base sizing of 2 in. is refined enough to use in the model.

Table 2. Mesh Sensitivity Helium Temperature Results

	Coarser	Middle	Finer
Base Size (in)	2.83	2.00	1.41
Number of Elements	13,506,620	24,865,429	33,498,546
	Maximum Temperature (°C)		
Inner Helium	210.79	208.33	208.29
Outer Helium	187.11	185.51	185.49

Steady State Results

Once the simulation had reached steady state, meaning that temperature results and residuals were no longer changing with iteration, the average and maximum temperatures were sampled in the regions of interest and are shown in Table 3. These results represent the temperatures within the dry storage configuration under ambient temperatures. The helium temperature of the DOESC located at the center of the over canister reached a peak value of 209°C and averaged at around 184.5°C. The helium temperatures of the eight other DOESCs reached a peak value of 186°C and averaged at around 163°C. In all the DOESCs, the maximum helium temperature was reached near the top of the innermost fuel element.

Table 3. Steady State Temperature Results for Regions of Internal Components.

	Steady State Temperature Results (°C)	
Region	Average	Maximum
Inner Fuel	187.87	208.36
Inner Helium	184.18	208.33
Inner Canister	159.89	182.69
Outer Fuel	167.07	185.55
Outer Helium	162.86	185.51
Outer Canister	137.72	169.29
Argon	116.55	181.71
Over Canister	95.84	171.39

Fully Engulfing Flames Results

After running the simulation for 30 minutes under hypothetical accident conditions, the temperatures were recorded again (Table 4). A comparison of the results of Table 4 with the steady state results of Table 3 indicates that the temperatures of the inner DOESCs and dry storage configuration internal regions are only insignificantly affected by the outside temperature increase (i.e., the outer helium region's average temperature increased by around a degree while the maximum temperatures had little to no change). However, the temperatures in the outer regions of the configurations, such as the over canister and its argon backfill, increased significantly, with average temperatures increasing by 88% and 78% and maximum temperatures increasing by 132% and 99%, respectively.

Table 4. Average and Maximum Temperature Results of the Internal Regions after 30 Minutes of Being Exposed to 800°C Ambient Temperatures.

	Temperature (°C)	
Region	Average	Maximum
Inner Fuel	187.90	208.36
Inner Helium	184.26	208.35
Inner Canister	160.33	182.75
Outer Fuel	167.18	185.55
Outer Helium	163.62	185.51
Outer Canister	142.39	169.34
Argon	177.52	324.23
Over Canister	146.92	347.36

Upon examining the results at the 30-minute mark, the ambient temperature was reduced to 38°C, while temperature sampling continued. This "cool-down" phase was considered because it was expected that the heat dissipation of the over canister and argon would have residual effects on the temperature of the internal components. For instance, while the temperatures of the over canister and argon region began declining immediately, the temperatures of the internal components continued to rise as the dry storage system was allowed to cool. Table 5 shows the maximum temperature reached by each region, and the time the temperature was reached. Once the temperature of the innermost regions had reached the maximum temperature at 22.3 hours of simulation time from the start of the 800°C ambient condition, all the temperatures were decreasing. The total temperature increase to the inner and outer helium regions was less than 6°C which indicates that the effect of the residual heat from the engulfing flames is insignificant to the internal components.

Table 5. Maximum Temperature and Simulation Time of Occurrence.

Region	Maximum Temperature (°C)	Time of Occurrence (hr)	Difference from Steady State Condition	Difference from Temperature Peak During Fire
Inner Fuel	212.47	22.3	4.11	4.11
Inner Helium	212.45	22.3	4.12	4.10
Inner Canister	187.47	15.5	4.78	4.72
Outer Fuel	190.88	10.8	5.33	5.33
Outer Helium	190.87	10.8	5.37	5.36
Outer Canister	175.36	8.6	6.07	6.02
Argon	324.23	0	181.71	0
Over Canister	347.36	0	175.97	0

Blocked Vent Port Results

The temperature results from the helium regions from the transient simulation with blocked vent ports showed that the maximum temperature of the innermost helium region reached 316°C at 17 days and 343°C at 29 days after the vent ports of the dry storage system were plugged as shown in Figure 3.

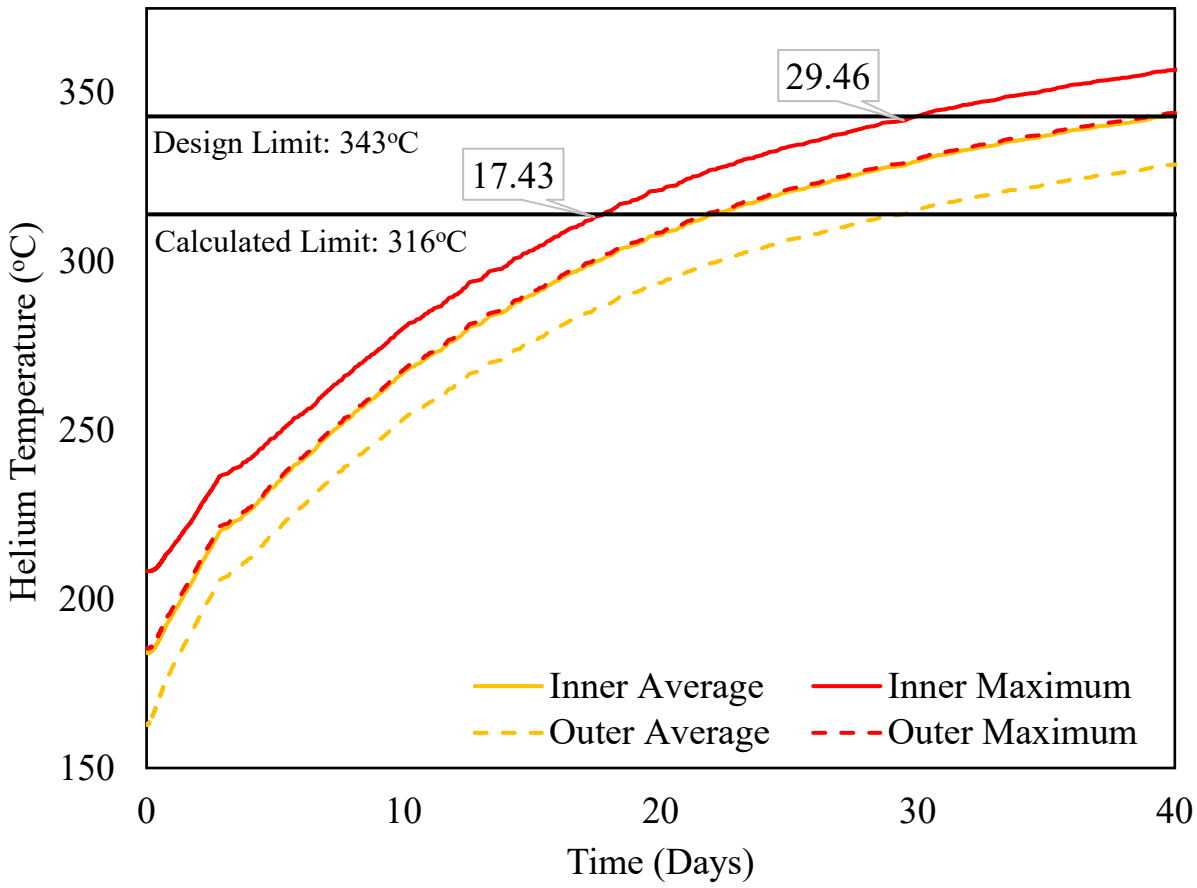


Figure 3. Helium Region Temperatures vs. Time Since the Blockage of Vent Ports.

Conclusions

The following conclusions can be drawn from the findings of this study:

- In the considered fire scenario, the peak helium temperature reaches 208.38°C which is below the preliminary DOESC design temperature of 343°C and below the critical base case scenario temperature of 316°C. Therefore, there is no concern of over pressurization resulting from the fire scenario.
- Compared with the steady state results, it can be concluded that the fully engulfing fire increases the peak helium temperature only marginally, and the post-fire cool down phase shows an insignificant increase in the helium temperature.
- In the considered blocked vent port scenario, the peak helium temperature continues to increase after 40 days. The critical base case scenario temperature of 316°C could be

exceeded after ~17 days of vent port blockage, and the preliminary DOESC design specification temperature of 343°C could be exceeded after 29 days of vent port blockage.

Citations

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