Mitigate Strategy of Very High Temperature Reactor Air-ingress Accident

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1. Introduction

A critical safety event of the Very High Temperature Reactor (VHTR) is a loss-of-coolant accident (LOCA). Since a VHTR uses graphite as a core structure, if there is a break on the pressure vessel, the air in the reactor cavity could ingress into the reactor core. The worst case scenario of the accident is initiated by a double-ended guillotine break of the cross vessel that connects the reactor vessel and the power conversion unit. The operating pressures in the vessel and containment are about 7 and 0.1 MPa, respectively. Therefore, once the break of the cross vessel is initiated, the helium coolant of the reactor is discharged into the containment. In the VHTR, the reactor pressure vessel is located within a reactor cavity which is filled with air during normal operation. Therefore, the air-helium mixture in the cavity may ingress into the reactor pressure vessel after the depressurization process.

In this paper, a commercial computational fluid dynamics (CFD) tool, FLUENT, was used to figure out air-ingress mitigation strategies in the gas-turbine modular helium reactor (GT-MHR) designed by General Atomics, Inc.

2. GT-MHR Design Features

2.1 Design Simplication

As shown in Fig. 1, the pressure vessel and the power conversion units are located underground. This part of the building is constructed as cylindrical silo and isolated from the rectangular part of the building above the ground. The wall structures, doors and any other barriers are designed to separate the fluid flow from the silo portion and the rectangular part of the reactor building. In the event of the large pipe break in the closed portion of the reactor building, the gases in the closed portion could move to any compartment through the entire building and released to atmosphere through relief valves.

Since each compartment is not air sealed and the compartments are connected to each other, the fluid could flow to other compartments. A simplified CFD model is made by dividing it into two parts, cavity 1 and 2, as shown in Fig. 2. The volume of vessel, cavity 1 and cavity 2 were set to 530 m^3 and 24,470 m^3 to conserve the containment volume, respectively. When a double-ended guillotine break of the cross vessel was considered for this analysis, the discharged helium would fill the compartment in the vessel and power conversion unit (PCU) first. Therefore, the cavity volume was set to the combined volume of the cavity volume of PCU and reactor vessel.

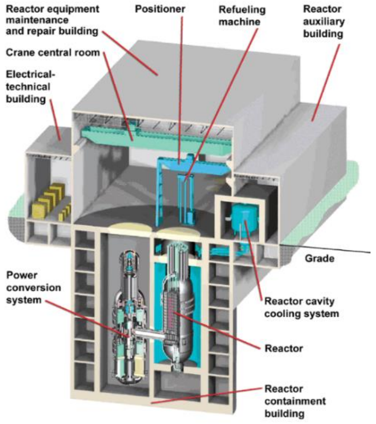


Fig. 1 GT-MHR below grade installation

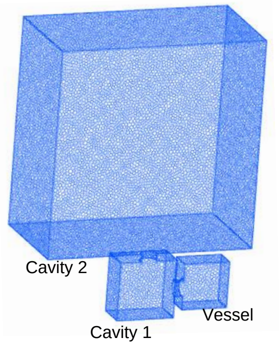
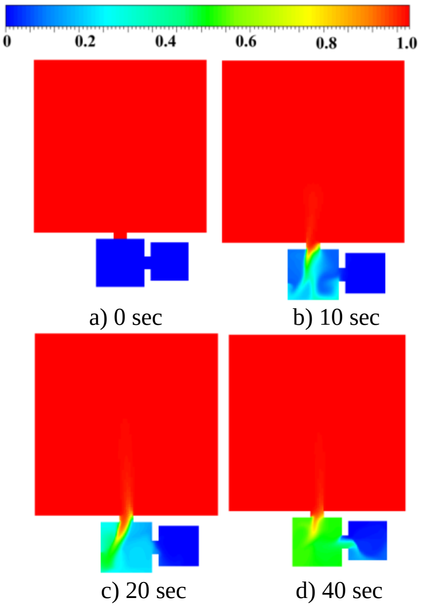


Fig. 2 GT-MHR CFD model

2.2 Air-ingress Analysis

Fig. 3 shows the CFD simulation result of how the air can flow back to the reactor cavity. The simulation is initiated when the reactor vessel and cavity 1 are filled with 100% helium, and cavity 2 is filled with 100% air at 300K and atmospheric pressure. This initial condition represents the state when depressurization is terminated. Even though the concentration in cavity 1 and cavity 2 would not be 100% helium and 100% air, respectively, after the depressurization process.



a) 0 sec b) 10 sec

c) 20 sec d) 40 sec

Fig. 3 Air mass fraction change over time – air flow back to cavity 1

It is simply the initial condition to identify how heavier air flows into the lower level. The simulation results show that the heavier air located in the higher compartment could easily flow to the lower compartment through the free open surface. Therefore, the multiple compartment design of the reactor building might interrupt the air-ingress accident; however, eventually air will flow back to the reactor cavity which is located lower in the ground in the building and also could flow to the reactor vessel.

2.3 Air-ingress Mitigation Strategy

Air is the heaviest gas in the reactor building during the air-ingress accident; air could flow back to the reactor cavity as shown in Fig. 3. Therefore, if the reactor cavity is filled with heavier gas than air, it would be hard to establish the air flow back to the reactor cavity. Among the inert gas listed in Table 1, Argon is heavier than air and it is more affordable than krypton and xenon, therefore, it would be the best material to prevent air ingresses by filling the reactor cavity.

Table 1 Inert Gas Density and Price

	Atomic number	**Density (kg/m^3)**	**Price $(\$/m^3)$**
Helium	2	0.16	8.34
Nitrogen	7	1.12	6.43
Neon	10	0.81	1,617.20
Argon	18	1.60	8.01
Krypton	36	3.37	1,110.78
Xenon	54	5.89	7,072.00

During the depressurization stage, the reactor cavity will be mixed with the depressurized helium; therefore, initiating argon gas at the beginning of the depressurization process would waste it. For that reason, the argon injection needs to be initiated near the end of the depressurization. To make this injecting process become passively activated, the injection port could be blocked by utilizing the pressure of the reactor system. The normal operating pressure of GT-MHR is 7.0 MPa. If there is a break on the pressure boundary the pressure of the reactor will decrease.

To investigate the argon injecting process, CFD model used to have the injection port at the bottom left of cavity 1 as shown in Fig. 4.

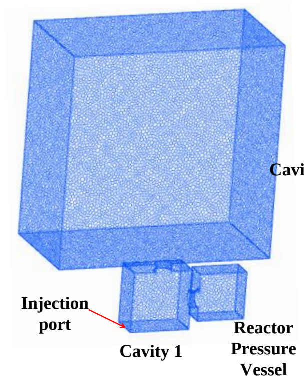


Fig. 4 Compartmentalized CFD model with argon injection port at the bottom of cavity 1.

During the depressurization process, the gas species in cavity 1 would be moved to the neighboring compartment. Therefore, if the injection into cavity 1 starts in the early stage of the depressurization process, it would make the density of the gas outside cavity 1 increase, and the driving forces to cavity 1 from the other compartment would contain more air and argon. Therefore, the argon injection should initiate near the end of the depressurization stage.

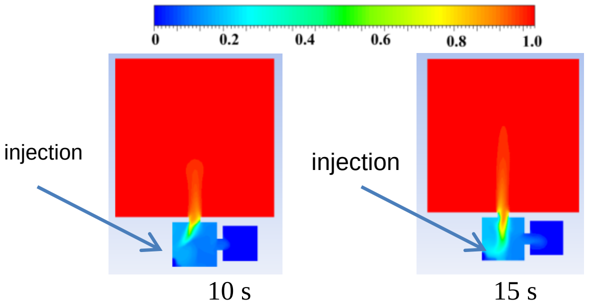
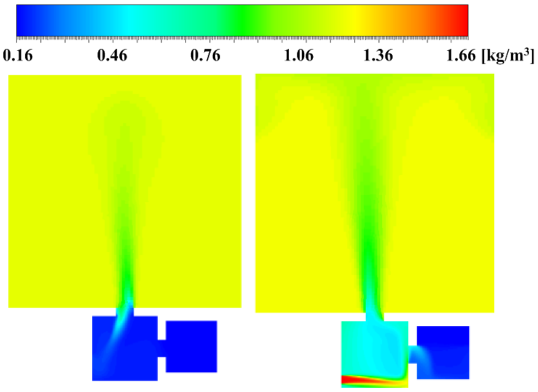


Fig. 5 Mass fraction of air (inert gas injection)

Figure 5 shows the results cavity 1 and reactor vessel are initially filled with 100% helium, and cavity 2 is filled with 100% air at room temperature and atmospheric pressure. Since during the depressurization process, 92% air moves to the neighbor compartment and fills with depressurized helium. Therefore, filling 100% helium would not make big differences. Initially 1 kg/s of argon injected into the cavity 1. However, as shown in the Fig5, air flow back in to the cavity 1 is observed.



(a) no argon injected b) argon injected

Fig. 6 Density contour at 20 sec

At the initial stage of argon injection, there are large density differences between cavity 1 and cavity 2. As a result, it would take quite a bit of time to increase the density of the gas in cavity 1 after the initiation of argon gas injection. Therefore, air flow back to cavity 1 is observed in this simulation.

To decrease the time it takes to increase the density of gas mixture in cavity 1, the argon injection rate is increased to 10 kg/s. Even though the injection rate increased, the density of gas mixture in cavity 1 is still lower than cavity 2 at 20 seconds after the argon injection is initiated as shown in Fig. 6 b). However, the air flow back to cavity 1 is not observed in Fig. 7, since the injected helium pressurizes cavity 1 so that the air in the cavity 2 cannot flow into cavity 1.

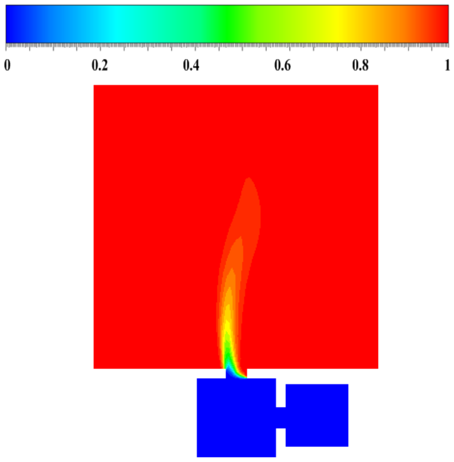


Fig. 7 Air mass fraction contour at 20 sec
(Argon injection rate 10 kg/s)

The argon injection model simulation gave insight on how to inject argon gas into the reactor cavity. The argon injection needs to be initiated near the end of the depressurization process to minimize argon gas loss by the depressurized helium from the reactor vessel. In addition, the argon injection rate needs to make cavity 1 pressurized to prevent air flow from cavity 2 when the density in the cavity 1 is lower than cavity 2.

3. Conclusions

After depressurization, there is almost no air in the reactor cavity; however, the air could flow back to the reactor cavity since the reactor cavity is placed in the lowest place in the reactor building. The heavier air could flow to the reactor cavity through free surface areas in the reactor building. Therefore, Argon gas injection in the reactor cavity is introduced. The injected argon would prevent the flow by pressurizing the reactor cavity initially, and eventually it prevents the flow by making the gas a heavier density than air in the reactor cavity. In addition, a hinge type physical block closed by gravity is introduced. The gate opens when the reactor cavity is pressurized during the depressurization and it closes by gravity when the depressurization is terminated so that it can slow down the air flow to the reactor cavity.

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