Air-Cooled RCCS Failure Mode and Effect Analysis for a VHTR

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1. Introduction

A very high temperature reactor (VHTR) is a candidate GEN-IV reactor for hydrogen production as well as high-temperature process heat generation. When a postulated cooldown accident occurs, the core decay heat is removed by conduction through the graphite reflector and by radiation and natural convection from the reactor vessel. The reactor cavity cooling system (RCCS), which receives the heat transferred from the vessel, removes heat from the reactor cavity by natural circulation of outside air. Although the potential failure possibility of the RCCS is very low, the failure modes and effects are performed to demonstrate the inherent safety feature of the catastrophic free design concept.

2. Passive Reactor Cavity Cooling System

The air-cooled RCCS removes heat from the reactor cavity in a passive manner by the natural convection of outside air through the cooling panel located in the reactor cavity. As shown in Fig.1 the inlets/outlets are located above grade, and the cooling panel, which consists of cold downcomer and hot riser, surrounds the reactor vessel below grade.

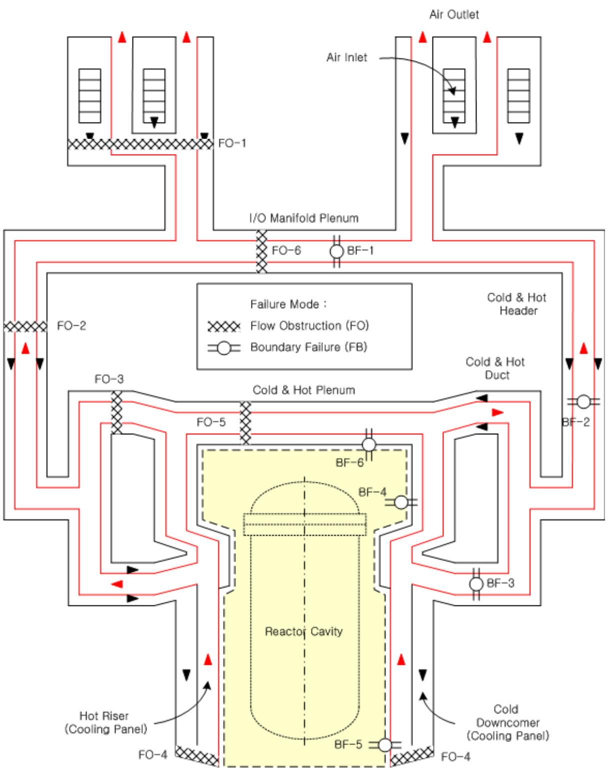

Fig. 1 RCCS Configuration and Postulated Fault Locations

The inlet openings of the I/O structures supply cold atmospheric air, and the outlet openings facilitate the exhaust of hot air back to the atmosphere. The hot air carries heat from the reactor cavity. The concentric cold/hot ducts transport cold and hot air between the I/O structures and the cooling panel. The outer cold duct transports cold air from the I/O structure to the cooling panel while the inner hot duct transports hot air from the cooling panel to the I/O structure.

The cold air, entering the cooling panel which completely surrounds the reactor vessel, flows down by gravity to the bottom of the reactor cavity via the cold downcomer section, and starts up the riser section which faces the reactor vessel. The air then begins to collect the heat radiated and convected from the reactor vessel. The buoyancy imparted to the air due to heatup causes the air to move upward towards the top of the reactor cavity through the riser section of the cooling panel.

3. RCCS Failure Modes and Ranges

As a passive system, the RCCS has very few potential failure modes. The faulted system conditions which could potentially result in a failure of the RCCS to perform its allocated functions have been determined to fall into the following three categories:

- Loss of structural integrity, including inlet/outlet structure damage or RCCS boundary faults
- Obstruction of a normal air flow path within the RCCS
- Air flow instability within the system caused by an adverse atmospheric condition (e.g., strong wind)

The faulted condition scenarios which have been considered and analyzed by the GAMMA+ system thermo-fluid analysis code [1] are listed at Table 1.

Table 1 RCCS Failure Modes

Failure Mode	Faulted Range	Faulted Condition
Boundary Failure Mode		
BF-1	0~3.85 m^2	Break at I/O manifold plenum
BF-2	0~3.52 m^2	Break at cold/hot header
BF-3	0~2.84 m^2	Break at cold/hot duct
BF-4	0~2.29 m^2	Panel opening at the cold plenum
BF-5		Panel opening at the risers
BF-6		Panel opening at the hot plenum
Flow Obstruction Mode		
FO-1	100% blockage	Blockage at inlets/outlets
FO-2		Blockage at cold/hot header
FO-3		Blockage at cold/hot duct
FO-4	0~2.29 m^2	Blockage at panel inlet
FO-5	100% blockage	Blockage at cold/hot plenum
FO-6		Blockage at I/O manifold plenum
Strong Wind Effect		
Wind	0~60 m/s	Wind blows perpendicular to inlets/outlets

At the un-faulted normal operation condition the RCCS air temperatures at the inlet and outlet are 40°C and 130°C, respectively. The calculated air flow rate by natural circulation is 9.8 kg/s. The heat removal rate by outside air is 894 kW for the prismatic core VHTR of 350MW thermal power [2].

4. RCCS Failure Mode and Effect Analysis

For the failure modes BF-1, 2 and 3 the cold air flows into the hot side through the break opening by resulting in flow reduction into the cooling panel. Thus the heat removal rate by outside air decreases as the break area increases as shown at Fig. 2. The rapid reduction in the figure is due to flow reversal at the air outlet.

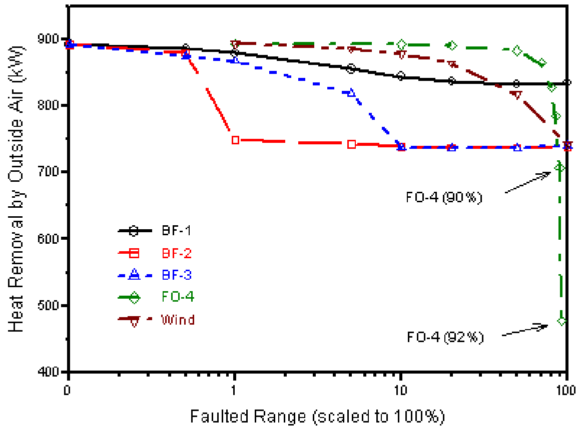

Fig. 2 Calculated RCCS heat removal rates by outside air for the RCCS faulted scenarios

For the failure modes BF-4, 5 and 6 the hot air in the reactor cavity is discharged into the cooling panel thus affecting the flow rate and temperature of the outside air. This failure mode does not affect the RCCS performance under the normal operation. During the depressurized event the reactor building may remain at about 0.9 bar above the atmospheric pressure after the open-then-close action of a relief vent. Since the pressure balance between the reactor cavity and the outside air is established in a short period, however, the effect on RCCS is negligible.

For the failure modes FO-1, 2 and 3 the inherent redundancy of the flow path design ensures a negligible adverse effect. When a flow path is blocked the normal air flow is established though the unaffected flow path. For the complete blockage the reduction in the heat removal rate by outside air is within 2%.

For the failure mode FO-4 the flow path at the bottom of the cooling panel is blocked thus reducing the air flow into the cooling panel. As shown at Fig. 2 the heat removal rate decreases mildly up to the 90% blockage thus resulting in a negligible adverse effect. Above the 90% blockage the heat removal rate rapidly drops due to low flow rate, less than half of nominal flow rate, and the flow instability at the air outlet section.

For the failure modes FO-5 and 6 the complete blockage of the connection plenum does not affect the RCCS performance due to the redundancy design feature.

The strong wind effect is assessed less than that of other worst failure modes.

The failure modes of the passive air-cooled RCCS are bounded by the case of FO-4 90% flow obstruction corresponding to 20% reduction in the heat removal rate and its effects are negligible. Above the FO-4 90% flow obstruction the reactor vessel temperature exceeds the SA-508 temperature limit (538°C) during the depressurized cooldown event, as shown at Fig. 3. Nevertheless the fuel temperature is below the temperature limit (1600°C) by assuring the fuel integrity.

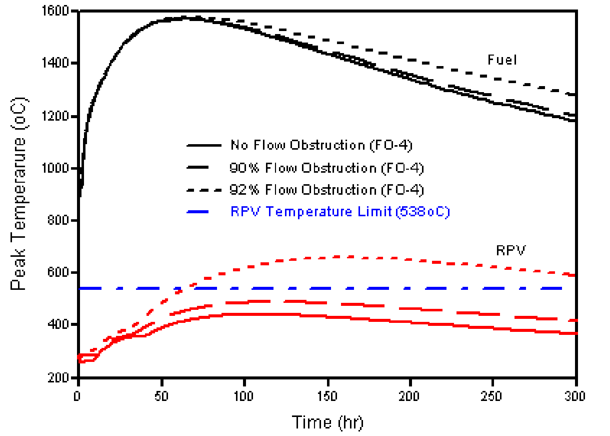

Fig. 3 Predicted maximum temperatures during the depressurized conduction cooldown event

5. Conclusions

The air-cooled RCCS failure modes and effects are analyzed using the GAMMA+ system TF analysis code for the prismatic core VHTR of 350MWth. The RCCS failure modes are bounded by the case of 90% flow obstruction at the bottom of the cooling panel. Below the 90% flow obstruction its effects are negligible and the fuel and reactor vessel integrity is assured.

Acknowledgements

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[2] N.I TAK, H.S. LIM, J.S. JUN, and C. YOON, "System Thermo-Fluid and Containment Analysis Models for NGNP 350MWth Conceptual Design," NHDD-RD-CA-10-028, Rev.0, December 2010.