Sodium Fire Analysis in the PGSFR Containment

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1. Introduction

The Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR) is a typical pool-type SFR with the power of 150 MWe. The PGSFR uses metallic fuel to make use of inherent safety characteristics of metallic fuel. All the primary components (fuel and core, four intermediate heat exchangers, and two primary heat transport pumps) and sodium are arranged inside reactor vessel. This pool-type reactor minimizes the possibility of LOCA by eliminating the connecting pipe and ensures a mild temperature and pressure transition during transient conditions [1].

In PGSFR molten sodium is used as a coolant, since it has excellent thermos-physical properties such as a high thermal conductivity. However the sodium has potential sodium fire risks when sodium leak occurs in the containment where the molten sodium is contained, it should take account of reducing the impact of the sodium fire in designing the containment in view point of pressure and temperature for enhancing the safety of SFR. This paper evaluates the pressure and temperature behavior in the containment during a postulated sodium leakage using CONTAIN-LMR code [2].

2. Containment and Sodium Fire Protection Design

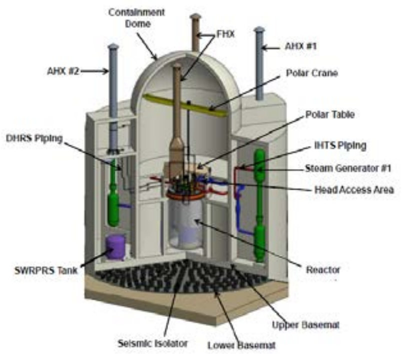

Figure 1 PGSFR Containment

The containment is designed to establish an effective barrier against the uncontrolled release of radioactivity to the environment and to assure that the functional containment design conditions important to safety are not exceeded for as long as postulated accident conditions require. The PGSFR design incorporates a reinforced concrete containment that is steel-lined on its inner surfaces that is an essentially leak-tight barrier against uncontrolled release of radioactivity. The containment is designed with margin to withstand pressures and temperatures resulting from a postulated sodium leakage.

The sodium fire protection system consists of prevention, mitigation and extinguishment features to reduce a potential risk of sodium fire. For the prevention of sodium fire, sodium pipe located in the containment is double-walled as shown in Figure 2. The released sodium is collected from the gap between an inner and outer pipe and delivered to a sodium collection tank. For the mitigation of sodium fire, the compartments are designed with steel liner plates on the floor to prevent the sodium-concrete reactions. Sodium catch pan and suppression decks are also incorporated into these compartments for reducing the long-term compartment temperature and pressure after sodium fire. For the extinguishment of sodium fire, dry powder is used for the suppression of a sodium fire [3].

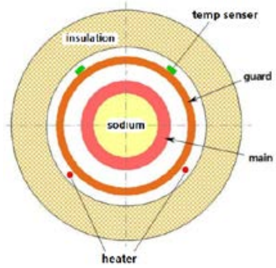

Figure 2 Double walled piping design concept

3. Design Basis Accident

Sodium systems inside containment consist of intermediate heat transfer system, decay heat removal system, primary sodium purification system and others. All sodium piping inside containment is designed as follows: double walled pipes and inert environment condition, inner piping designed in accordance with LBB criteria, capability of the leak detection system to provide an early warning of any breach in the piping boundary, and leaked sodium drain system.

Sodium piping is classified as moderate energy piping according to the BTP MEB 3-1 acceptance criteria [4] and NUREG-0968 [5]: 1) Sodium piping operates about 550℃(1022˚F) while the sodium boiling temperature is 883℃(1624˚F) at atmospheric pressure. Therefore, the stored energy of sodium piping is much low, 2) Sodium piping pressure is well below 19.3 kg/cm^2 (275 psig) which is the pressure criteria to classify the piping as high energy piping system. Therefore, pipe break is not considered on the sodium piping but crack is only postulated to be occurred in containment. The crack size is determined as one half of the pipe wall thickness multiplied by one half of the pipe inside diameter.

In the event of sodium leakage from the inner pipe, the outer guard pipe prevents sodium from spilling upon the compartment floor.

Therefore a simultaneous rupture (crack) of inner and outer pipe is a very low probability event and it is considered as a beyond design basis accident. Nevertheless simultaneous double pipe rupture (crack) is conservatively assumed as design basis accident for PGSFR containment design.

4. Analysis Methodology and Modelling

The containment pressure and temperature analyses are performed using the CONTAIN-LMR computer program. It analyzes the thermodynamic phenomena and aerosol behavior in the containment during sodium fire caused by sodium leakage. In this analysis, the containment is modeled into two regions such as the atmospheric region and the sodium liquid region. The leaked sodium reacts with oxygen and causes a sodium pool fire. The generated heat is transferred between the liquid and atmosphere region and increase pressure and temperature in the containment

Mass and energy release from sodium pipe crack

Sodium leakage and a sodium pool fire are assumed to occur inside of the annular compartment located below the operating deck and housing the piping of the intermediate heat transport system. The time history sodium release rate is shown in Figure 3, and the total amount of released sodium is 3,625.1 kg during 95.2 seconds.

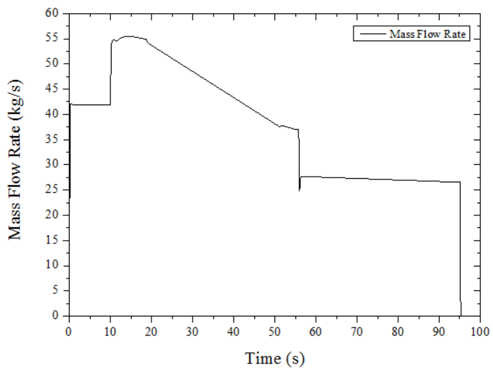

Figure 3 Sodium Release Rate versus Time

In addition, it is assumed that 468,680 W of heat is generated in the reactor and equipment inside the containment and transferred to the containment atmosphere.

Containment

The containment is a reinforced concrete shell structure consisting of a cylindrical wall and a partial hemispherical dome, and is designed to prevent sodium-concrete reaction by attaching a steel liner to the inner structure of the containment. In this analysis the containment is modelled as a single volume, and the concrete structures are considered as heat sink. Containment free volume is the total volume of the containment, excluding the volume of structures and equipment. Since the sodium fire is dependent on the amount of leaked sodium and oxygen, the maximum free volume is taken into account for the containment pressure and temperature analysis. It is 37,830 m^3. Initial conditions are conservatively assumed in order to maximize the calculated pressure or temperature under normal operating conditions. These are 101,352.0 Pa (14.7 psia), 48.9℃.

Containment heat removal

In the case of sodium fire, the heat of the containment atmosphere is removed by heat transfer to the passive heat sink, which is internal structures, floor, cylindrical wall, dome structure. These passive heat sinks absorb heat in the containment atmosphere, thereby suppressing a rise in containment pressure and temperature. The thermal characteristics of the passive heat sink in this analysis are assumed as the same data applied to the APR1400. In order to predict the temperature gradient of the concrete structure during sodium fire, the floor structure is subdivided into 40 nodes, and the cylindrical wall and the dome concrete are subdivided into 5 cm intervals.

The containment air conditioning system is operated to remove the atmospheric heat of the containment during normal operation, and does not perform safety functions in an accident. Therefore the heat removal by this system is not considered in the analysis.

Light weight insulating concrete

When high temperature sodium is released to form sodium pool at the floor of the containment, and the pool fire occurs and persists, the temperature of the sodium pool rises rapidly, exceeding the concrete temperature limit of the design basis accident (176 ℃). To prevent this, light weight insulating concrete with 3 cm thickness is installed between the steel liner and the concrete structure to limit heat transfer from the sodium pool to the concrete structure. The thermal properties of the insulating concrete are shown in Table 1.

Table 1 Thermal properties of insulating concrete [6]

Parameter	Value
Density (kg/m3)	1,041.2
Compressive strength (Mpa)	6.2
Thickness (cm)	3
Thermal conductivity (W/mK)	0.692 (310.92 K) 0.363 (477.64 K)
Specific heat (J/Kg-K)	1,674.72 (310.92 K) 1,088.57 (477.64 K)

<u>Sodium fire mitigation</u>

In order to reduce the amount of sodium participating in the sodium pool fire, a 2 inch drain pipe is installed on the collected sodium pool floor to transfer the pool sodium to a sodium fire suppression deck installed in a lower area of the containment.

5. Analysis Results and Conclusions

The containment pressure and temperature due to the sodium pipe cracks in the intermediate heat transfer system is analyzed by the CONTAIN-LMR to evaluate the thermal behavior of the sodium pool fire in the PGSFR containment. In this analysis the containment is modelled as a single volume, and the concrete structures are considered as heat sink. The initial conditions such as atmospheric temperature, pressure, humidity, and concrete temperature are conservatively selected. The insulation concrete with 3 cm thickness and 2 inch drain pipe are assumed in this analysis. The types of sodium fires are assumed as pool type.

The analysis results for the sodium pool fire are shown in Figure 4 through 11. The maximum atmospheric pressure is 0.1095 MPa (15.9 psia) after 970 seconds, and the maximum atmospheric temperature is 76.48℃ after 1,300 seconds. The maximum temperature of the floor concrete in sodium pool is 164 ℃ after 235 seconds respectively. At this time, among 3,625 kg, which is the total amount of the leaked sodium, the amount of the combusted sodium is 547 kg, and the amount of sodium drained into the suppression deck through the pipe is calculated as 3,078 kg. Finally the PGSFR containment is designed with sufficient margin to withstand pressures and temperatures resulting from a postulated sodium pool fire.

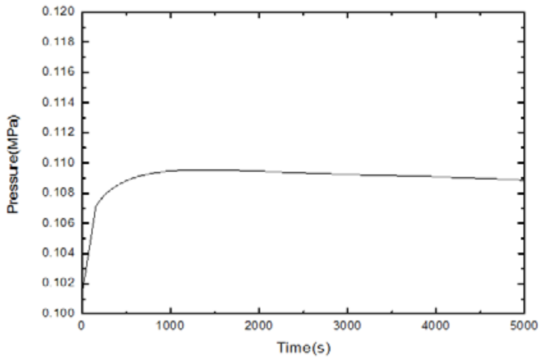

Figure 4 Containment Atmosphere Pressure versus Time

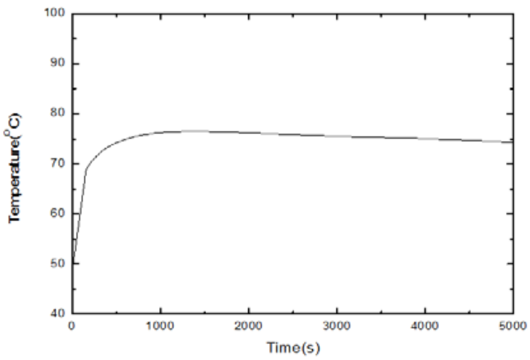

Figure 5 Containment Atmosphere Temperature versus Time

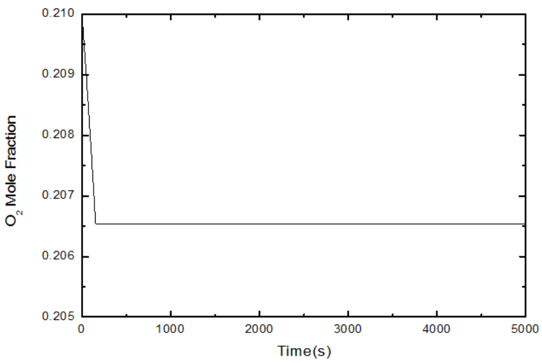

Figure 6 Containment Oxygen Mole Fraction versus Time

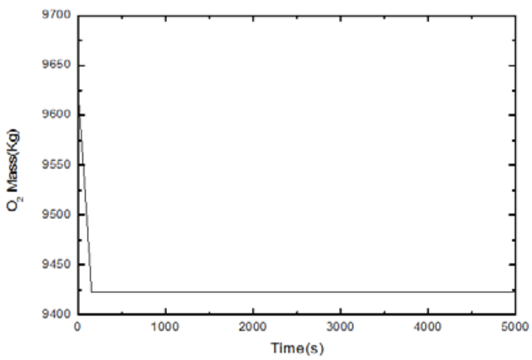

Figure 7 Containment Oxygen Mass versus Time

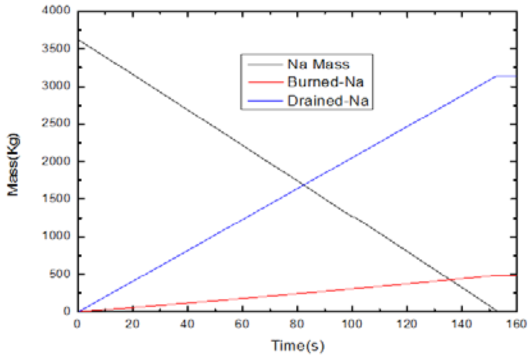

Figure 8 Containment sodium mass versus Time

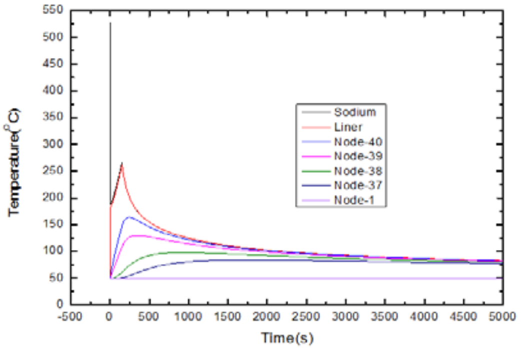

Figure 9 Containment Floor Concrete Temperature versus Time

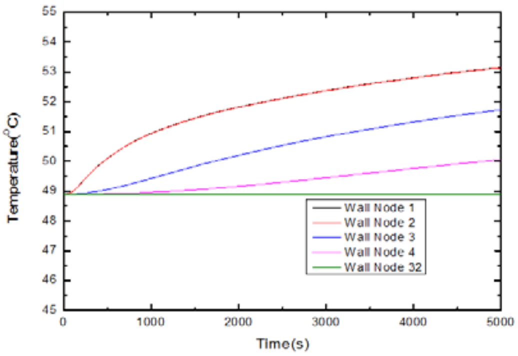

Figure 10 Containment Wall Concrete Temperature versus Time

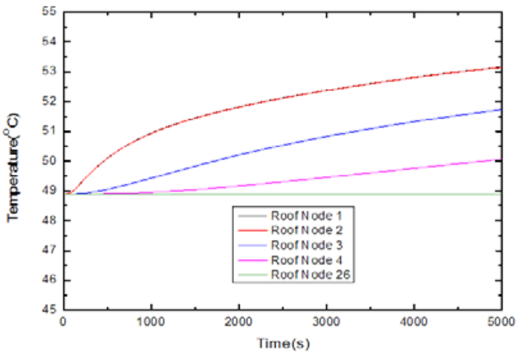

Figure 11 Containment Dome Concrete Temperature versus Time

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[4] BTP MEB 3-1, "Postulated Rupture Locations in Fluid System Piping inside and outside Containment", Revision 1, USNRC, 1981

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[6] CRBRP PSAR Chapter 15, Table 15.6.1.4-2, Material Properties Used for the Spray SOF IRE Analysis