

Flow rate 1,053 gpm

Velocity 0.231 m/s
Inlet temp. 632.2 °C
Outlet temp. 654.4 °C

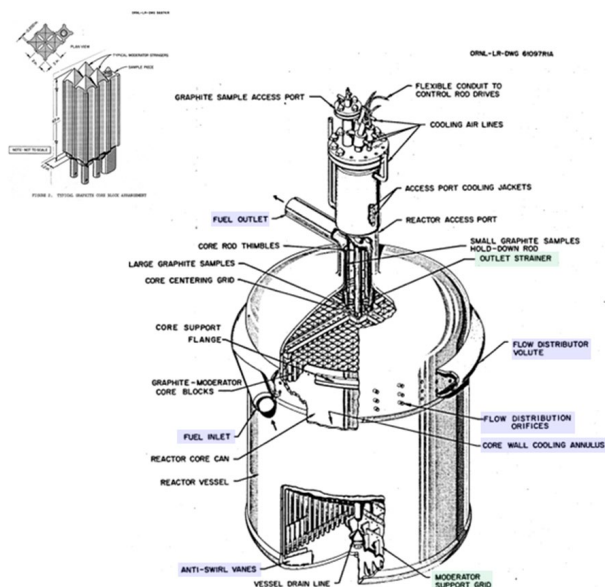


Fig. 3. MSRE Reactor Vessel

4. Design Consideration for the Reactor Vessel Internal

The thermal-hydraulic design targets of the internal structures are reviewed and suggested as follows. Reynold number, temperature, buoyancy force, instability shall be carefully considered in the design, calculation, and verification test. The laminar, transition or turbulent flow field could exist in each flow path.

Flow distribution at the core inlet

· Generally, the shape of the flow distribution at the core inlet is designed to be almost the same as the shape of the radial power distribution of the core to make the core outlet temperature distribution uniform. It is assumed that the core outlet temperature distribution is uniform. Two types of flow distributions are commonly applied. One is the flap shape, the other is the parabolic shape with the highest velocity at the core center region. Since this flow distribution is closely related to the internal structure design, especially in the core support plate and lower plenum, accurate design targets are required.

· Flow distribution for each fuel inlet shall be provided as a design requirement and result.

· Uncertainty shall be provided.

· It should be designed to minimize the fluctuation of the flow.

· It should be designed without any oscillation. (Temperature profile shall be considered together.)

· If multiple pipes including Reactor Coolant Pumps (RCPs) are connected to the RV, such as a general

Pressurized Water Reactor (PWR), the design shall be evaluated with the number of operating RCPs [4], [5].

· The basic design is generally carried out using the CFD (Computational Fluid Dynamics) analysis. The verified test results are required for the Construction Permit (CP) to guarantee the design input for the safety and performance analysis.

Temperature distribution of the molten salt and structure

· The downcomer is designed to limit the increase of the temperature in the reactor vessel wall. The heat is generated from the reactor vessel wall and molten salt because of the nuclear heating. Heat transfer characteristics are determined based on the flow fields.

· The flow fields in the downcomer are controlled by the volute, wall distance and downcomer flow guide.

· It should be designed without any oscillation. (Nuclear heating shall be considered together.)

· The basic design is generally carried out using the CFD analysis. The verified test results will be required for the CP to guarantee the stable flow fields. It is the design characteristic of the MSR. Therefore, the regulatory body will require the verified test results.

· Since the design margin is determined based on the reactor characteristics, it is necessary to discuss and determine the design parameters and tolerances related to the reactor safety. In the general PWR, the Departure from Nucleate Boiling Ratio (DNBR) is one of the factors to evaluate the integrity of the fuel cladding. This value is calculated through the temperature and pressure of the coolant on the fuel cladding. But, since the boiling temperature is sufficiently higher than the design and operating temperature of the Primary System, unlike the general PWR, the DNBR is not expected to be a critical parameter for the safety analysis. The temperature distribution in the pressure boundary components of the RV and Primary system is expected as the key design parameter.

Thermal-hydraulic characteristics

· The pressure loss and heat transfer coefficient are strongly influenced by Reynolds number. The laminar, transition or turbulent flow field could exist in each flow path.

· The CFD analysis will be carried out to calculate the flow fields, pressure loss, temperature distribution in the structure and molten salt. There is a limitation to assure the results of the CFD analysis in wide ranges of Reynolds number, especially in the transition region. Therefore, the verified test will be required to finalize the design.

· The steady-state and unsteady-state hydraulic loads on reactor vessel internals shall be calculated and these results are used for the mechanical design.

· It is necessary to check the unexpected formation of an unstable flow field.

The main flow path suggested is as follows.

Inlet Pipe → Volute → Downcomer including the Downcomer Flow Guide (Azimuthal Flow Guide) → Flow Distributor → Lower Plenum → Core → Upper Plenum → Outlet Pipe

5. Fuel Salt System Flow Band and Temperature

The Primary System is designed to provide the sufficient flow rate to the reactor core to remove the heat during the normal operation of the reactor in the Molten Salt Reactor. The Primary Pump is installed to provide the forced circulation flow. The design flow rate (or rated flow) of the Primary Pump shall guarantee the flow rate designed for the reactor thermal-hydraulic parameter. This flow rate is sometimes referred to as the thermal design flow rate (TDF). The flow rate of the Primary Pump is calculated based on the Primary System flow band design. 110% of the TDF is assumed as the Primary Pump design flow rate in consideration of the thermal design flow, measurement uncertainty, aging effect and allowable flow band for start-up operation as shown in Fig. 4 [6]. The description of each flow rate in the Primary System flow band is as follows.

- Thermal Design flow: Reference thermal-hydraulic design value
- Minimum Measured flow: Thermal design flow + Measurement uncertainty
- Minimum Allowable Flow: Minimum measured flow + Fouling effect of the components of the Primary System
- Best Estimated Flow (Primary Pump design flow rate): Minimum allowable flow + Allowable flow band
- Maximum Allowable Flow: Best estimated flow + Allowable flow band
- Maximum Predicted Flow: Maximum allowable flow + aging effect of the Primary system
- Maximum Design Flow: Maximum Predicted flow + Measurement uncertainty

This value is applied for the mechanical and thermal-hydraulic design flow rate of system, structures, and components (SSCs)

- Limiting Safety System Setting (Low, High)

These values shall be decided based on the safety and uncertainty analysis

Measurement uncertainty: 5% of the measurement uncertainty is assumed based on design experience and engineering judgment (The calculation note shall be issued during the basic design stage) [6]. Generally, flow rate of the Primary System is calculated from the heat balance method because it is difficult to install the calibrated flowmeter in the Primary System. This calculated flow rate is set for each instrument such as the speed sensor of the Primary System, differential pressure transmitter of the component during the Hot Functional Test (HFT). The measurement uncertainty is evaluated from the uncertainty analysis based on the heat balance equation, measured values, uncertainty of each instrument, and heat losses.

Fouling effect: 2% of the flow rate decrease is assumed because of the fouling effects based on design experience and engineering judgment (The calculation note shall be issued during the basic design stage). Generally, flow rate is decreased if the pressure loss is increased. The fouling effects of the Primary System are considered. There is a high probability of the fouling effect at a low velocity.

Allowable flow band: $\pm 3\%$ of the uncertainties are assumed with the pump design flow rate as the center value based on design experience and engineering judgment (The calculation note shall be issued during the basic design stage). These values will be evaluated from the pump performance curve, system operating ranges and uncertainties of the system hydraulic resistance curve.

It is expected that the Variable Frequency Device (VFD) is adopted to the Primary Pump to control the flow rate. If the VFD is applied, these uncertainties could be decreased to about $\pm 1\%$ in consideration of the control range of the VFD. Nevertheless, $\pm 3\%$ of the uncertainties are still assumed for the conservative design approach.

Aging effect: 0.5% of the flow rate increase is assumed because of the aging effect based on design experience and engineering judgment (The calculation note shall be issued during the basic design stage). Generally, flow rate is increased if the pressure loss is decreased. This value reflects the design characteristics of the MSR. The increase of the flow rate during the plant operation is not considered in the general PWR and Research Reactor (RR)

On the other hand, the maximum design flow rate effects the temperature distribution in the Primary System.

Possible temperature program of the Primary System are assumed as shown in Fig. 5.

Core inlet and outlet temperatures with the flow rate is calculated.

Temperature ranges with flow rates shall be considered in the safety and performance analysis.

These temperature ranges with flow rates shall be also applied to the heat exchanger design.

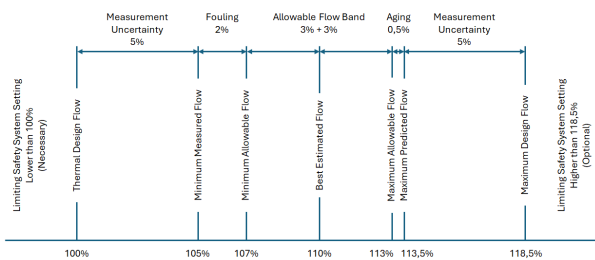


Fig. 4. Fuel salt system flow band

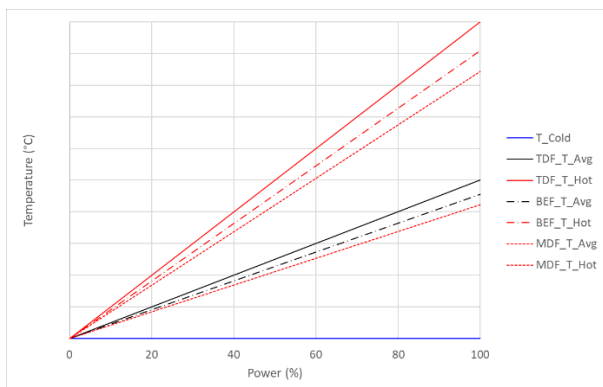
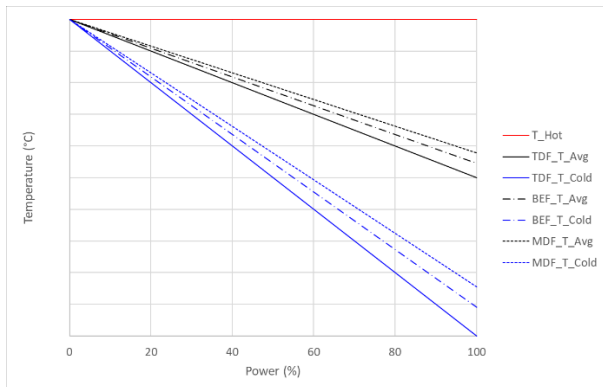
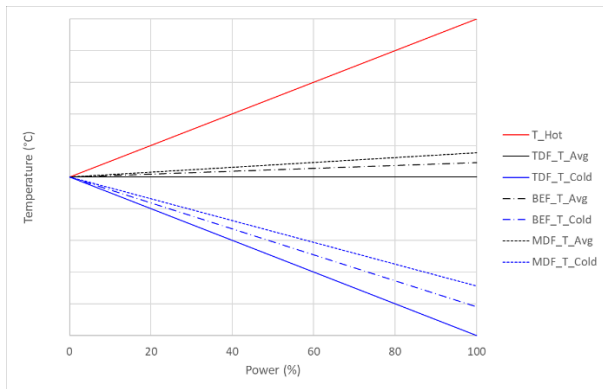
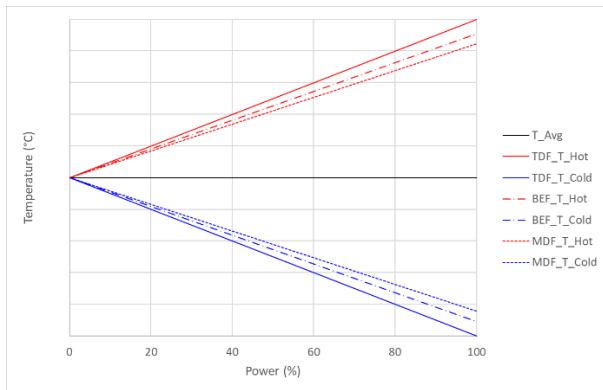


Fig. 5. Conceptual design of core inlet and outlet temperatures during a start-up sequence.

6. Conclusions

A design review of the MSRE primary system was conducted. In addition, the thermal-hydraulic design requirements for the reactor vessel of the MSR primary system were proposed, taking into consideration the designs of existing general PWR and RR. Furthermore, design approaches for the primary system flow rate and temperature were presented. These will be taken into account as the design proceeds during the basic design process.

REFERENCES

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