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# CODE SIMULATION OF A PRELIMINARY PASSIVE MODERATOR COOLING SYSTEM FOR CANADIAN SCWR CONCEPTUAL DESIGN

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## Abstract

A Passive Moderator Cooling System for the Canadian SCWR (supercritical water-cooled reactor), using a flashing-driven natural circulation loop, is being developed at AECL. A preliminary conceptual design of the passive moderator cooling system for normal operation was simulated using the CATHENA code. Major dimensions for the conceptual design of passive moderator cooling system were established. An operation map was constructed for the established dimensions to determine the operation power range of the conceptual design of passive moderator cooling system.

## 1. INTRODUCTION

Improved safety is an important objective in the development of advanced nuclear reactor technology under GIF (Generation IV International Forum). Canada is a member of GIF and is focusing on the development of the supercritical water-cooled reactor (SCWR).

A Passive Moderator Cooling System for the Canadian SCWR, using a flashing-driven natural circulation loop, is being developed at AECL [1], [2] and [3]. This passive design focuses on improving the role of the moderator as a passive heat sink during normal operation and in the unlikely event of an accident involving loss of coolant.

The conventional moderator in a CANDU type reactor operates with low-pressure heavy water in a cylindrical calandria vessel that serves as a back-up heat sink in the unlikely event of loss-of-coolant combined with loss-of-emergency core cooling (ECC). The moderator cooling system is used to remove heat deposited in the moderator during normal operation, mainly due to gamma and neutron heating. This heat, which is approximately 5% of reactor thermal power, is of the same order of magnitude as decay heat shortly following reactor shutdown; therefore, this system is sufficient to remove decay heat should the ECC system fail.

The existing moderator cooling system relies on pumps to remove heat deposited in the moderator during normal operation, and to remove decay heat during certain accident scenarios. Furthermore, existing CANDU type reactors require the moderator to operate with a certain degree of subcooling to avoid film boiling on the calandria tube if the pressure tube balloons into contact with the calandria tube following a LOCA (loss-of-coolant accident).

The role of the moderator can be significantly enhanced if a passive moderator cooling system using flashing-driven natural circulation is used. The flashing-driven passive moderator concept was demonstrated using scaled-down passive moderator cooling test loops [1] and [3]. The scaling methodology and instability mechanisms were investigated for flashing-driven natural circulation in a passive moderator cooling system [2] and [3].

In the Canadian SCWR design, the moderator operates slightly subcooled, which creates conditions such that two-phase flow can be generated by flashing as the flow rises from the calandria into a vertical riser, providing a significant buoyancy-driven force for recirculation.

A preliminary conceptual design for a passive moderator cooling system was developed for normal operation using the CATHENA code. Major dimensions for the conceptual design of passive moderator cooling system were established. An operation map was constructed for the established dimensions to determine the operation power range of the conceptual design of passive moderator cooling system.

## 2. A PRELIMINARY CONCEPTUAL DESIGN OF PASSIVE MODERATOR COOLING SYSTEM

In the passive moderator cooling concept, as the moderator fluid flows upward in the riser, flashing and vapour generation occur in the riser due to the decrease in pressure. This design feature makes it possible to remove moderator heat under both normal and accident conditions using natural convection flow. Furthermore, having the moderator temperature close to saturation provides the option of using the moderator heat for feedwater heating, which improves plant efficiency.

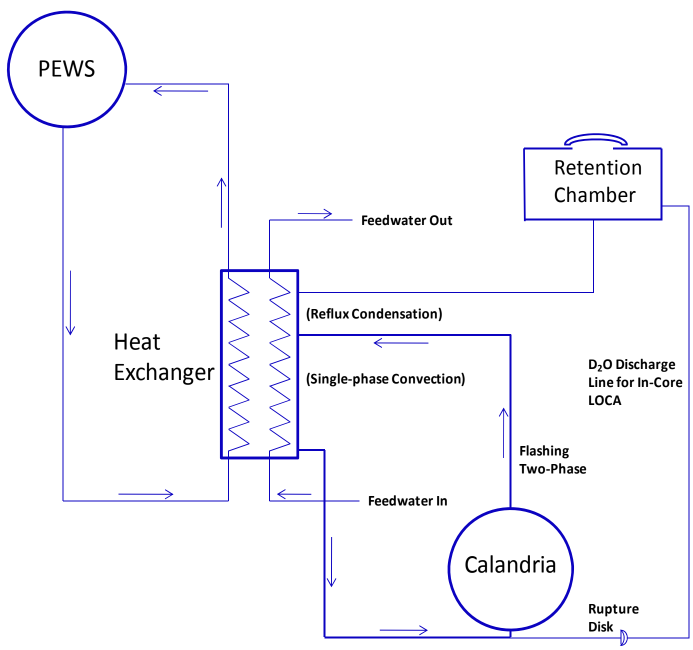


**Figure 1 A Preliminary Conceptual Design for Passive Moderator Cooling System**

A preliminary conceptual design for a passive moderator cooling system is shown schematically in **Figure 1**. Moderator heat is continuously removed from the moderator under normal operation[1]. The heat transferred to the moderator is rejected to heat exchangers that are cooled by feedwater and naturally circulating light water from an overhead passive emergency water system (PEWS) tank, which serves as a common ultimate heat sink for this and other passive removal systems.

Design parameters for the conceptual design of the passive moderator cooling system were established for normal operation, as presented in Table 1. The geometric design parameters and operating parameters (feedwater mass-flow rate, and inlet and outlet temperature, and the pressure at the top of retention chamber) were established. The flow parameters (for example, void fraction and mass-flow rate of the loop) are values predicted using the CATHENA code with the geometric and operating parameters listed in Table 1.

The passive moderator cooling system has two loops with a riser and downcomer each, and a calandria. The height and diameter of the riser are 8.1 m and 0.46 m, and those of the downcomer are 7.3 m and 0.3 m, respectively. The design moderator heat load under normal operation is 100 MW, and the calandria volume is 180 $m^3$. The calculated temperature at the calandria inlet in the downcomer is 58.4°C. The pressures at the calandria inlet and at the riser outlet are 366 kPa and 234 kPa, respectively, and the heavy water mass-flow rate of the moderator system is 333 kg/s.

Feedwater mass-flow rate in the heat exchanger is 500 kg/s, and the temperature at the inlet of feedwater is 20.0°C. In the current conceptual design, the heat exchanger is assumed to be functioning only by feedwater, without considering the cooling by the natural circulation with PEWS for simplicity. The cooling performance of heat exchanger with the feedwater determines the subcooling in the downcomer. For the same applied power to calandria, the subcooling in the downcomer increases as the cooling efficiency of heat exchanger increases. The cooling efficiency of heat exchanger depends on the mass-flow rate and inlet temperature of feedwater for the same heat transfer coefficient in the heat exchanger. The cooling efficiency increases as the mass-flow rate of feedwater increases or as the inlet temperature of feedwater decreases. Thus, either or both of the two parameters, mass-flow rate and inlet temperature of feedwater, can be adjusted as appropriate for the moderator design.

The current conceptual design allows two-phase flashing in the riser under normal operation, and is functioning with flashing-driven natural circulation. The void fraction at the outlet of riser is predicted to be 80% under normal operation. Void creation in the calandria is avoided under normal conditions to prevent unstable operation of the moderator loop. There is a transition from single-phase to two-phase at the start of the moderator loop (i.e., downstream of the calandria).

[1] Note that the moderator fluid is $D_2O$ (heavy water).

**Table 1**
**Design Parameters of a Passive Moderator Cooling System Under Normal Operation**

| Parameter | | Values in Passive Moderator Cooling System |
|---|---|---|
| Design Moderator Heat Load, MW | | 100 |
| Calandria | Volume ($m^3$) | 180 |
| | Diameter (m) | 6 |
| | Length (m) | 6.37 |
| Riser | Diameter (m) | 2 x 0.46 (2 loops) |
| | Height (m) | 8.1 |
| | Horizontal Length (m) | 7 |
| Downcomer | Diameter (m) | 2 x 0.3 (2 loops) |
| | Height (m) | 7.3 |
| | Horizontal Length (m) | 10 |
| Heat Exchanger Tube Size (m) | | 0.0136 x 3500 |
| Feedwater Mass-Flow Rate (kg/s) | | 500.0 |
| Feedwater Inlet Temperature (°C) | | 20.0 |
| Feedwater Outlet Temperature (°C) | | 68.9 |
| Pressure at Top of Retention Chamber (kPa) | | 113 |
| Moderator Heavy Water Flow Rate (kg/s)* | | 333 |
| Mass Flux in Riser ($kg/m^2s$)* | | 1003 |
| Mass Flux in Downcomer ($kg/m^2s$)* | | 2357 |
| Pressure at Calandria Inlet (kPa)* | | 366 |
| Pressure at Riser Outlet(kPa)* | | 234 |
| Temperature at Calandria Inlet (°C)* | | 58.4 |
| Subcooling at Calandria Inlet (°C)* | | 83 |
| Density Ratio**: $N_\rho = \frac{\rho_f}{\rho_g}$ | | 718 |
| Subcooling Number**: $N_{sub} = \frac{\Delta H_{sub}}{H_{fg}}$ | | 0.14 |
| Phase Change Number**: $N_{pch} = \frac{\dot{Q}}{\dot{m} H_{fg}}$ | | 0.15 |
| Froude Number**: $Fr = \frac{G^2}{\rho_f^2 l g}$ | Riser | 0.0116 |
| | Downcomer | 0.0709 |
| Quality at Riser Outlet (%)** | | 0.8 |
| Void Fraction at Riser Outlet (%)** | | 80 |

* Values calculated using the CATHENA code. ** Values calculated at the riser outlet.

## 3. SIMULATION OF CONCEPTUAL DESIGN

The conceptual design, as shown in **Figure 1**, was simulated with the given geometric and operating parameters in Table 1 using the CATHENA code. The heat exchanger of the loop was simulated by the CATHENA GENHTP model, which was used to model solid heat conduction for piping walls and their connection to the thermalhydraulic branches.

The simulation of heat exchanger was simplified by assuming that the heat exchanger is cooled only by feedwater, without considering the cooling by the natural circulation with PEWS. The primary side and the secondary side of the heat exchanger were modelled as pipe components with equivalent hydraulic diameters. The heat transfer surfaces between the primary side and the secondary side were modelled using "Hydraulic BCs" in GENHTP, which defines parameters that determine the heat transfer rates between the primary side and the secondary side of the heat exchanger. The calandria tank was modelled as a pipe component.

The conceptual design of passive moderator cooling system was simulated for normal operation conditions (partial and full power). The flow conditions of heat exchanger and initial conditions of calandria inlet and outlet temperatures for the simulation are presented in Table 2. The moderator power (thermal power to the moderator) was increased in steps from low power to the normal operation power of 100 MW.

**Table 2**
**Conditions of Feedwater in the Heat Exchanger and Calandria Temperature Initial Condition for the Simulation of Conceptual Design**

| | | |
|---|---|---|
| Feedwater in the Heat Exchanger | Mass-Flow Rate (kg/s) | 500 |
| | Inlet Temp. (°C) | 20.0 |
| | Outlet Temp. (°C) | 68.9 |
| Calandria (initial condition) | Inlet Temp. (°C) | 30.0 |
| | Outlet Temp. (°C) | 112.4 |

Figure 2 shows the time history of CATHENA predicted mass-flow rate with varying calandria power, covering single-phase flow to two-phase flow. The single-phase mass-flow rate increases as the calandria power increases up to 60 MW. At the calandria power of 70 MW, the mass-flow rate has a jump with a peak, which indicates an initiation of flashing, where single-phase flow is changed to two-phase flow as illustrated in the void fraction distribution in Figure 3. Void initiates at the calandria power of 70 MW. As the calandria power continues to increase beyond the power of void initiation, the mass-flow rate also increases stepwise.

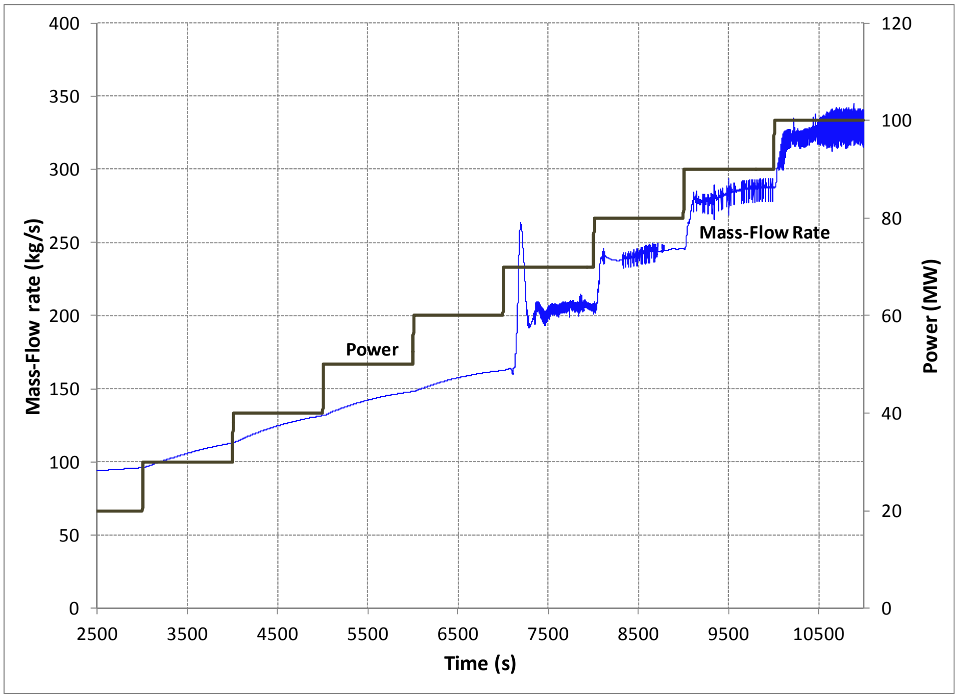


**Figure 2 Mass-Flow Rate with Varying from Low to Normal Calandria Power**

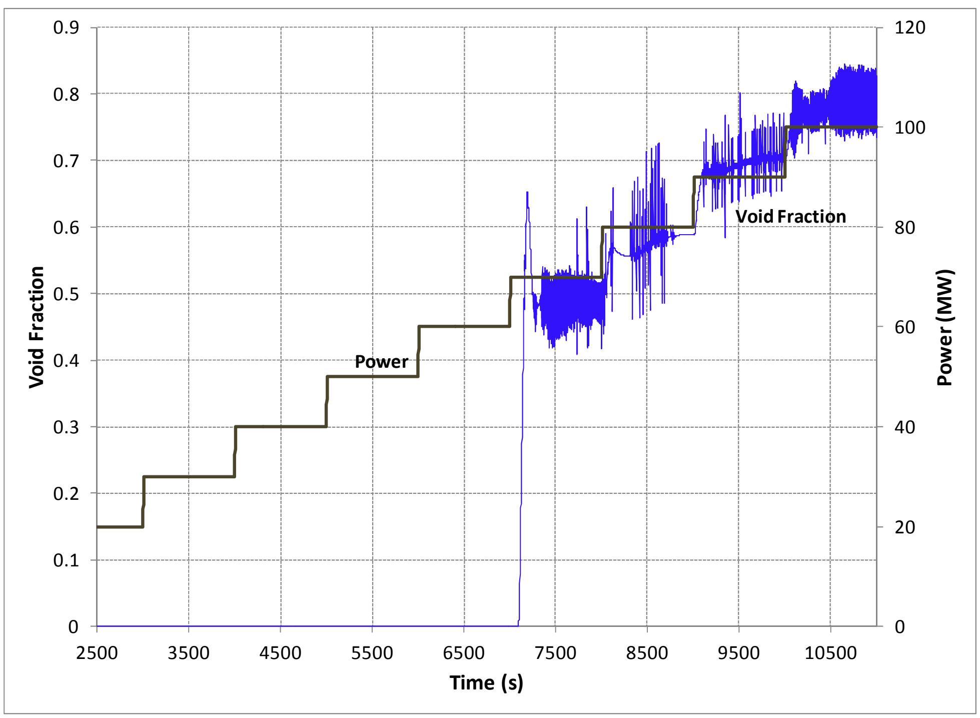


**Figure 3 Void Fraction at the Riser Outlet with Varying from Low to Normal Calandria Power**

## 4. OPERATION MAP OF PASSIVE MODERATOR COOLING SYSTEM

The operation power range is of importance to safely operate the passive moderator cooling system. The maximum operation power was defined as the power when flashing occurs in the whole length of the riser, without allowing void in the calandria. The conceptual design of passive moderator cooling system was simulated for different subcoolings at the inlet of calandria with varying calandria power from low power to power above the maximum power. The flow conditions of heat exchanger and initial conditions of calandria inlet and outlet temperatures for the case of simulation with a mass-flow rate of feedwater of 700 kg/s are presented in Table 3[2]. The moderator power was increased in steps from low power to the maximum power of calandria.

**Table 3**
**Conditions of Feedwater in the Heat Exchanger and Calandria Temperature Initial Condition for the Simulation (Mass-Flow Rate of Feedwater: 700 Kg/s)**

| | | |
|---|---|---|
| Feedwater in the Heat Exchanger | Mass-Flow Rate (kg/s) | 700 |
| | Inlet Temp. (°C) | 36.3 |
| | Outlet Temp. (°C) | 68.9 |
| Calandria (initial condition) | Inlet Temp. (°C) | 59.6 |
| | Inside and Outlet Temp. (°C) | 112.4 |

Figure 4 shows the time history of mass-flow rate of the passive moderator cooling system with varying calandria power for the simulation conditions (feedwater mass-flow rate of 700 kg/s). It is observed in Figure 4 that the mass-flow rate increases as the calandria power increases. The figure indicates the power at which two-phase flashing initiates in the riser. Figure 4 also exhibits oscillations of mass-flow rate with large amplitudes at high power. It is found that the mass-flow rate is oscillating with large amplitudes when void is generated in the calandria (void is propagated from the riser to the calandria). The continuing oscillations of the mass-flow rate are avoided under normal operation. In this study, the continuing oscillations are categorized as "unstable conditions". The power at which void starts to be created in the calandria (unstable-condition initiation) is indicated in Figure 4.

Figure 5 presents the time history of void fraction with varying calandria power for the same simulation conditions as those of Figure 4. At the power of 60 MW, void starts to be created, and at the power of 120 MW, the void fraction shows significant oscillation.

[2] The value of 700 kg/s was arbitrarily chosen to show the effect of mass-flow rate.

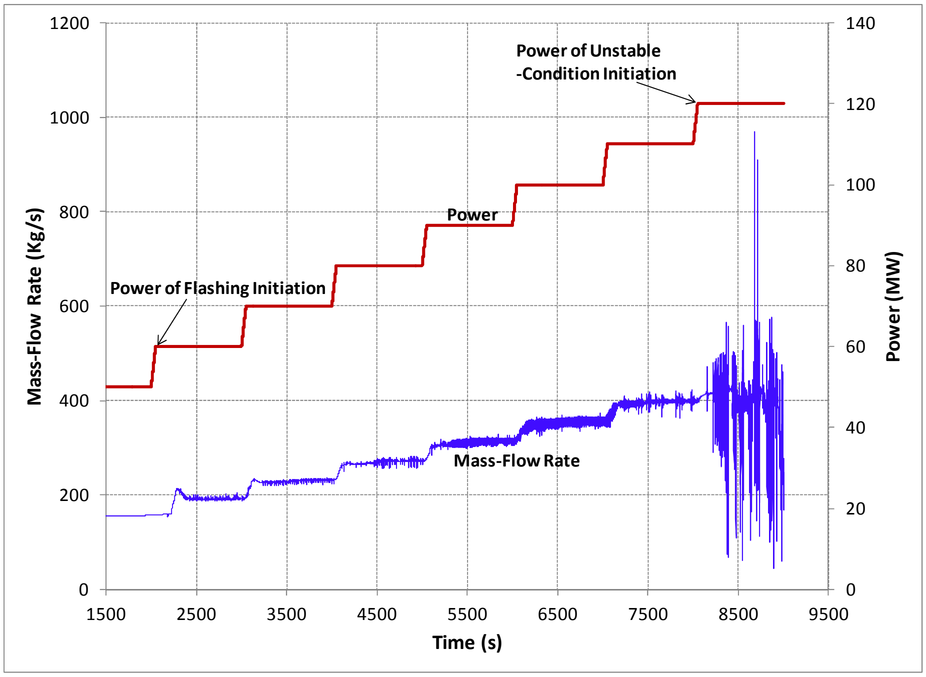


**Figure 4 Mass-Flow Rate with Varying Calandria Power**
**(Feedwater Mass-Flow Rate of 700 Kg/s)**

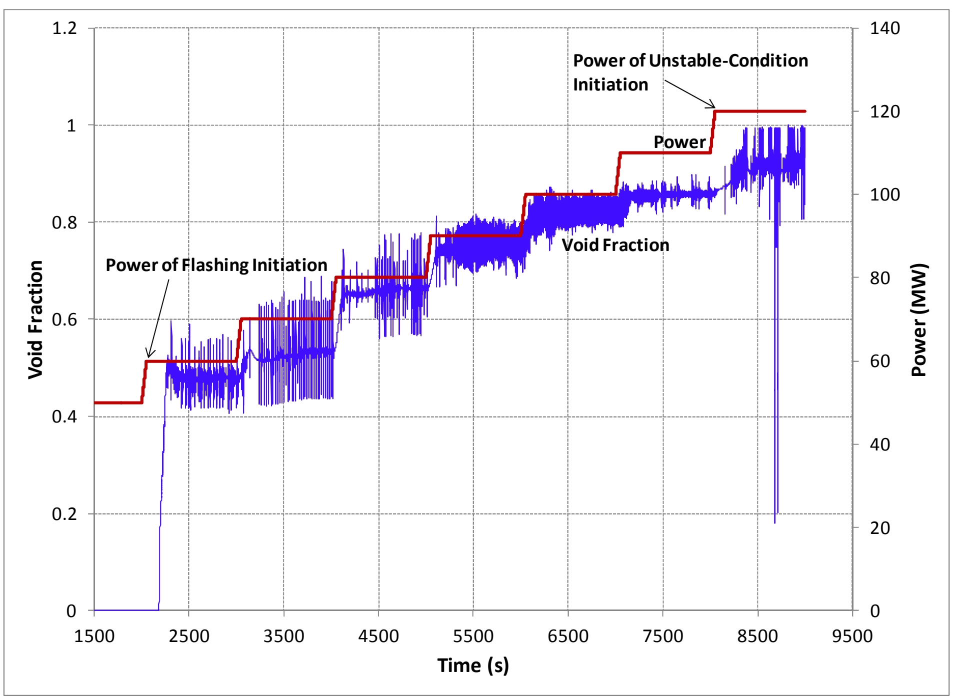


**Figure 5 Void Fraction at the Riser Outlet with Varying Calandria Power**
**(Feedwater Mass-Flow Rate of 700 Kg/s)**

Figure 6 shows an operation map for the conceptual design of passive moderator cooling system. This map was established using the fitted line for data points of "power of flashing initiation" and "power of unstable-condition initiation" with different feedwater mass-flow rates, calculated with the CATHENA code. This map illustrates a transition from single- to two-phase flow and an operation maximum power at a given calandria inlet subcooling. For example, for an inlet subcooling of 80°C, the power of transition from single- to two-phase is 41 MW and the maximum power for stable operation is 125 MW. The point of normal operation power of the present conceptual design is indicated in Figure 6. Note that the inlet temperature of feedwater is different between the normal operation calculation and the current operation-map calculation, and therefore the calandria inlet subcooling is different between the two cases at the same feedwater mass-flow rate and calandria power.

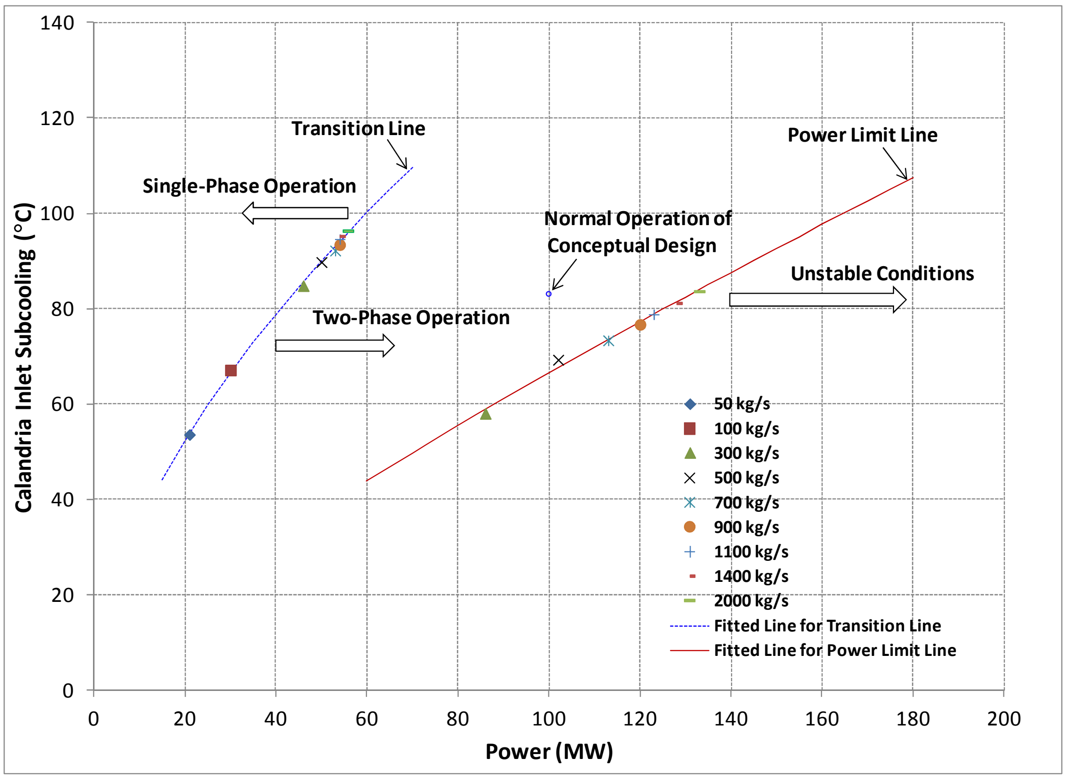


**Figure 6 Operation Map for Conceptual Design of Passive Moderator Cooling System Including Data Points Calculated with the CATHENA Code**

## 5. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are made:

- A preliminary conceptual design for a passive moderator cooling system was developed for normal operation using the CATHENA code. Major dimensions for the conceptual design of passive moderator cooling system were established.
- An operation map was constructed for the established dimensions to determine the operation power range of the preliminary conceptual design of passive moderator cooling system, covering low to maximum power.

- In the present flashing-driven natural circulation loop, the transition from single-phase flow to two-phase flow will generally involve flow oscillations. A criterion for acceptable flow oscillation may be required under normal operation and in the unlikely event of an accident. The acceptable level would depend on the geometry of loop and components of passive moderator cooling system.
- Tests are required to confirm the operation map with a test loop in which flow can be throttled and pressure can be controlled. The test results will provide information on the operation map including how to control or prevent the instabilities in the flashing-driven natural circulation.

## 6. NOMENCLATURE

| Symbol | Description | Unit |
|---|---|---|
| $g$ | acceleration of gravity | $m/s^2$ |
| $G$ | mass flux | $kg/m^2s$ |
| $H$ | enthalpy | kJ/kg |
| $\ell$ | axial length | m |
| $\dot{m}$ | mass-flow rate | kg/s |
| $\dot{Q}$ | calandria power | kW |

**Greek**

| | | |
|---|---|---|
| $\Delta H$ | characteristic enthalpy rise | kJ/kg |
| $\rho$ | density | $kg/m^3$ |

**Subscripts**

| | |
|---|---|
| *f* | saturated liquid |
| *fg* | latent heat of vaporization |
| *g* | saturated vapor |
| *sub* | subcooling |

## 7. REFERENCES

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