Preliminary analysis on the inadvertent opening of spring-assisted spool valve due to leakage

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1. Introduction

The innovative Small Modular Reactor (i-SMR) is characterized by the adoption of passive safety systems to enhance plant safety [1]. These systems are designed to function without external power or operator action [2,3]. The Passive Emergency Core Cooling System (PECCS) is an example of this design philosophy which is designed to ensure adequate core cooling following a loss-of-coolant accident (LOCA).

The PECCS performs its primary safety function by initiating a depressurization of the Reactor Coolant System (RCS) with the Emergency Depressurization Valves (EDVs) [1]. This process enables the subsequent establishment of a stable, long-term coolant recirculation loop through the Emergency Recirculation Valves (ERVs). The successful operation of the PECCS depends on a set of hydraulically operated, spring-assisted spool valves. They are required to actuate precisely under accident conditions while maintaining a leak-tight seal during normal operation to preserve the RCS pressure boundary. An inadvertent opening of these valves could initiate an undesirable plant transient.

A potential operational concern is the effect of leakage from the high-pressure chambers that hold the valves in their closed position. Such a leak could lead to a gradual depressurization of the chambers, potentially reducing the closing force and causing an unintended valve behavior. Therefore, predicting the dynamic behavior of the valves under such off-normal conditions is critical for ensuring plant safety.

Previous studies have introduced the SEMICOM methodology, which couples the MARS-KS system thermal-hydraulic code with an explicit solver for the valve's mechanical equations of motion, to analyze the dynamic behavior of these valves [4,5]. While effective for system-level transients, this approach has a key limitation in that it does not account for the pressure changes resulting from the volumetric variations in the hydraulic chambers as the spool moves. This simplification can affect the accuracy of resolving the rapid pressure transients that characterize hydraulic valve actuation. To address this, a dedicated numerical analysis model was developed using MATLAB, which allows for a more detailed and direct simulation of the hydraulic phenomena governing valve movement.

This study performs a basic analysis of the dynamic response of the PECCS valves to a postulated leakage condition using a MATLAB code. The analysis investigates the behavior of the main valve and the Spurious-Opening Protection Module (SOPM) under varying leakage rates, with the objective of identifying the conditions under which the main valve opens, irrespective of the SOPM's behavior.

2. Valve modeling

2.1 Valve Configuration

The valve system under consideration is as shown in Figure 1. It consists of a main valve and a Spurious-Opening Protection Module (SOPM), which are connected by a horizontal flow path. In this study, it is assumed that the postulated leak occurs from this horizontal flow path. The main valve spool, comprising upper and lower disks, is a downward-opening design. Its movement is guided by a retainer that also defines its travel limits. Fluidic connections with the RCS and the SOPM are established through a series of orifices perforated in the retainer and the lower disk. The SOPM, also a downward-opening design with an upper disk and a lower guide structure, acts as a protective barrier to prevent the inadvertent actuation of the main valve. For the purpose of dynamic analysis, the internal volumes of this integrated valve assembly are discretized into several control volumes.

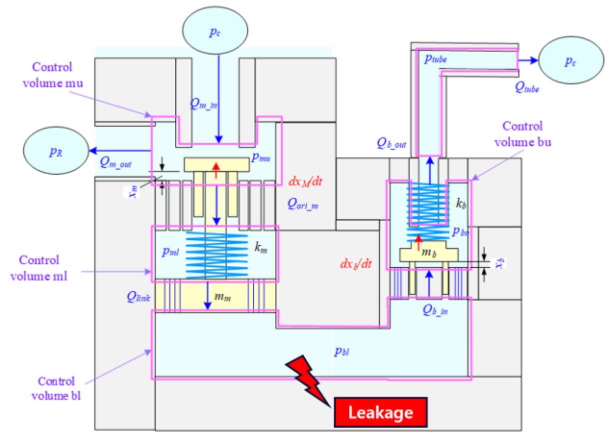

Figure 1. Schematic of the PECCS Valve System.

2.2 Governing Equations

The dynamic behavior of the spools for the main valve and the SOPM is described by their respective one-dimensional equations of motion.

For the Main Valve spool:

$$m_m \ddot{x}_m + c_m \dot{x}_m + k_m x_m = F_{p-m} + F_{m-m} \quad (1)$$

For the SOPM spool:

$$m_b \ddot{x}_b + c_b \dot{x}_b + k_b x_b = F_{p-b} + F_{m-b} \quad (2)$$

In these equations, *m* is the mass of the spool, *c* is the viscous damping coefficient, *k* is the spring constant, and y, $\dot{y}$, $\ddot{y}$ represent the spool displacement, velocity, and acceleration, respectively. F_p is the net force from hydraulic pressure on the spool surfaces. The subscripts *m* and *b* denote the main valve and SOPM, respectively.

2.3 Numerical Method

The numerical analysis was performed using an inhouse code developed in MATLAB software, based on the methodology detailed in a previous study [6]. The model is formulated as a system of coupled ordinary differential equations (ODEs), combining the equations of motion for the spools with the Pressure Rise Rate (PRR) equations for each hydraulic control volume. The PRR equation is defined as:

$$\frac{dp}{dt} = \frac{\beta}{V}\left(\sum Q_{in} - \sum Q_{out} - \frac{dV}{dt}\right) \quad (3)$$

Where β is the bulk modulus of the fluid, representing the fluid's resistance to compression, *V* is the control volume, and *Q* represents the volumetric flow rates. This equation links the rate of pressure change in a volume to the net flow and the rate of volume change due to spool movement (dV/dt).

This system of ODEs is solved using the ode15s solver in MATLAB. This solver is specifically chosen because the system is numerically "stiff." The stiffness arises from the wide disparity in time scales between the rapid hydraulic pressure transients and the much slower mechanical motion of the valve spools. The ode15s solver is a variable-order solver designed for stiff differential equations and is effective at maintaining numerical stability and computational efficiency for such problems.

2.4 Leakage Scenario

A leakage scenario was established to evaluate the potential for inadvertent opening of the main valve. The scenario is based on the Reactor Coolant System (RCS) leak rate, an inherent operational characteristic of Pressurized Water Reactors (PWRs) that provides a realistic basis for the analysis. For context, conventional PWRs typically have a technical specification limit of 1.0 gpm, while advanced SMRs like NuScale often consider a lower rate of 0.5 gpm. Accordingly, this analysis first evaluates the valve's response to a 0.1 gpm, and subsequently investigates higher rates to determine the design margin. To model this, the PRR equation for the leaking chamber is modified to include an additional leakage outflow term, Q_{leak}:

$$\frac{dp_{leak}}{dt} = \frac{\beta}{V_{leak}}\left(\sum Q_{in} - \sum Q_{out} - Q_{leak} - \frac{dV_{leak}}{dt}\right) \quad (4)$$

The initial condition assumes the plant is at normal operating pressure, with the reactor pressure vessel at 15.5 MPa and the containment vessel at 0.2 MPa. The main valve is initially closed, and the SOPM is open.

3. Results and Discussion

3.1 Model Validation

To verify the MATLAB-based model, its results were compared against those from the previous SEMICOM methodology[4,5]. The same LOCA pressure transient condition analyzed with SEMICOM was simulated using the MATLAB model. Figure 2 shows the comparison of the SOPM spool displacement between the two models.

As shown in the figure, the overall dynamic behavior of the SOPM, such as the timing of its closing and reopening, is similar in both analyses. However, the SEMICOM result exhibits significant oscillations, whereas the MATLAB result shows a more stable, non-oscillatory behavior. This difference is attributed to the fact that the SEMICOM method does not account for the pressure changes resulting from the volumetric variations in the hydraulic chambers as the spool moves. The MATLAB model, which incorporates this effect, is therefore considered to more accurately represent the physical damping within the system. Based on this comparison, it was confirmed that the MATLAB model appropriately describes the fundamental dynamic behavior of the valve and is suitable for the subsequent leakage analysis.

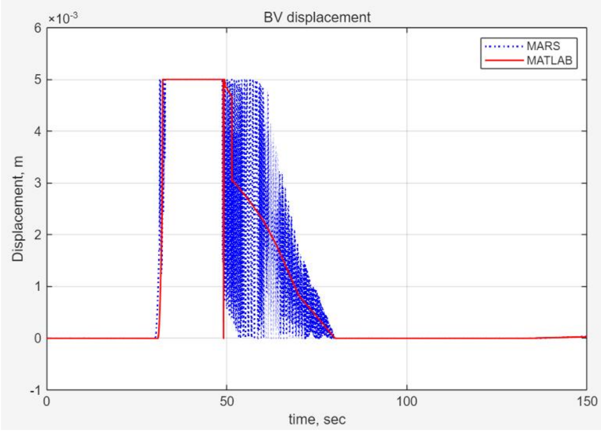

Fig. 2. Comparison of SOPM spool displacement between SEMICOM and MATLAB models.

3.2 Valve Behavior according to Leakage Scenario

The analysis of the main valve 's response to a postulated leak, initiated at t=1 second, was conducted by examining the spool's displacement, the pressure differential across it, and the net force acting on the spool. The results show that the main valve exhibited no movement for leakage rates up to 100 gpm, which is well above the RCS leak rate of 0.5 gpm for advanced SMRs. As illustrated in Figure 3, the main valve spool shows no displacement until the leakage rate reaches a critical value of 107 gpm, at which point it actuates.

It is noteworthy that while the main valve remained closed, the SOPM exhibited some movement at higher leakage rates (50 gpm and above). This is because the leak causes a pressure drop in the interconnected SOPM upper chamber and trip valve line. The relatively high pressure maintained on the main valve side then acts on the SOPM, creating a pressure differential that pushes its spool slightly in the closing direction.

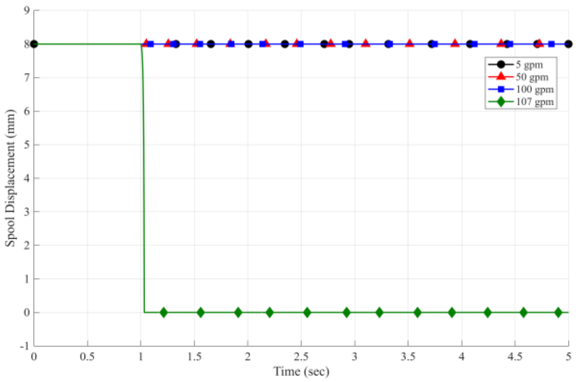

Fig. 3. Main valve spool displacement for various leakage rate.

To understand the mechanism behind this behavior, the pressure in the leaking chamber was investigated. Figure 4 shows that as the leakage rate increases, the steady-state pressure in this chamber decreases. This pressure drop creates an increasing downward force on the main valve spool; however, this force alone was insufficient to overcome the combined closing forces (e.g., spring force, control pressure). A significant pressure collapse to approximately 6.8 MPa occurs only at the 107 gpm rate, which corresponds to the point of main valve actuation.

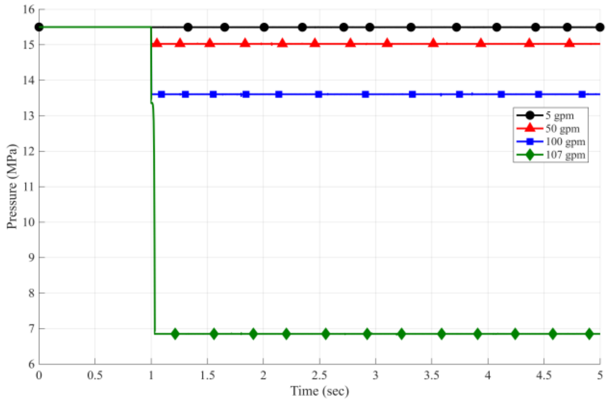

Fig. 4. Pressure differences between main chamber and leaking chamber according to leakage rate.

To identify the cause of actuation, the net force on the main valve spool was analyzed. This net force, which is the sum of all hydraulic, mechanical, and gravitational forces, remained in the closing direction (positive value) for all leakage rates up to 100 gpm. At the 107 gpm threshold, the force balance shifted, and the net force reversed direction to become negative, thereby driving the valve open. This confirms that the valve's actuation is strictly governed by the net force balance, which is only overcome at a significantly high and physically unrealistic leakage rate.

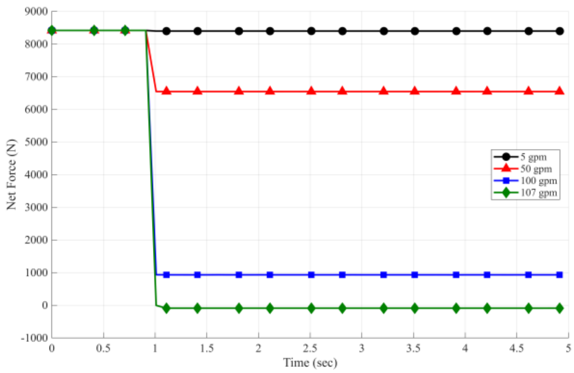

Fig. 5. Net force acting on main valve spool according to leakage rate.

4. Conclusions

This paper presents a preliminary analysis of the potential for inadvertent opening of a PECCS main valve due to leakage. The results indicate that the valve system shows significant robustness against such an event. The main valve remained closed until the leakage rate reached 107 gpm, a flow rate considered far beyond a credible leakage condition. Based on these preliminary findings, it is concluded that an inadvertent opening of the main valve is highly unlikely under realistic operational conditions.

However, this study has limitations that highlight the need for future work. The numerical model requires further refinement and validation, and the analysis was based on a preliminary valve design since the final i-SMR specifications are still under development. Future analyses must incorporate more realistic conditions for a comprehensive safety assessment. This includes modeling dynamic pressure boundaries where containment pressure and temperature evolve in response to the leak, which will provide a more accurate representation of the forces acting on the valve.

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