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Numerical Analysis of Overpressure Transient during Cold Shutdown Operation for APR1400 Nuclear Power Plant

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1. Introduction

During cold shutdown status, reactor coolant pressure boundary (RCPB) can be more brittle than during normal operation due to low coolant temperature. Therefore, ASME code describes specified requirements as allowable pressure for materials of RCPB for low temperature condition. RCPB should be protected during the condition as well because, if it fails, radioactive material can be released. ASME section III appendix G stipulates that maximum allowable pressure of reactor coolant system is 20% of hydrostatic test pressure which means the maximum allowable pressure below lowest service temperature. [1]

Generally we determine most severe mass-addition or energy-addition transients arisen by operator errors, malfunction of components or other causes for initiating events of LTOP (low temperature overpressure protection) analysis. According to safety analysis report for APR1400 [2], most severe transient for mass addition begins from startup of one charging pump and four high pressure safety injection (HPSI) pumps at the same time and, on the other hand, most severe transient for energy addition begins from startup of one reactor coolant pump and, as a results of it, heat transfer from secondary side of SG filled with higher temperature water to primary side of SG. If RCS pressure increases and reaches a set pressure of LTOP relief valves, installed on suction pipe of shutdown cooling system (SCS), the valves perform the function of RCPB protection during cold shutdown status.

This study aim to analysis overpressure transients during cold shutdown status for APR1400 and to confirm capacity of LTOP valve.

2. Analysis Methodology

2.1 Assumptions

Conservative assumptions in this analysis are as follows

1) No credit for operator action during 10 minutes
2) Single failure of LTOP valve
3) Solid operation
4) No volume of interconnected system
5) Initial RCS temperature is the same as refueling temperature.

2.2 General equations

We derived the governing equations to estimate the performance of LTOP. These equations are composed of mass and energy conservation equation for one volume of reactor coolant system. The conservation equations are as follows

$$V_{RCS}\frac{d\rho_{RCS}}{dt} = 4\times\rho_{HPSI}\cdot Q_{HPSI}+\rho_{CH}\cdot Q_{CH}-\rho_{RCS}\cdot Q_{RV} \quad \text{.........(1)}$$

$$V_{RCS}\frac{d(\rho_{RCS}\cdot h_{RCS})}{dt} = \dot{q}_{SG\to RCS}+\dot{q}_{decay}+\dot{q}_{pzr}$$
$$+4\times h_{HPSI}\cdot\rho_{HPSI}\cdot Q_{HPSI}+h_{CH}\cdot\rho_{CH}\cdot Q_{CH}-h_{RCS}\cdot\rho_{RCS}\cdot Q_{RV} \quad \text{.........(2)}$$

In above equations, the density and enthalpy of water is derived from water property table of interesting region using regression method as follows;

$$\rho_{RCS} = -0.0028\times T^2-(0.0001985P+0.1409)\times T+(0.0481P+1001.6) \quad \text{.........(3)}$$

$$h_{RCS} = 4.1977\times T+3.3406 \quad \text{.............................(4)}$$

The result from solving the conservation equations gives the average pressure and temperature inside reactor coolant system. Maximum pressure inside reactor coolant system is the sum of the average pressure and static head at the bottom of core region.

2.3 Component Modelling

Each term in right side of equation (1) means added mass transfer rate by HPSI pump, charging pump, and released mass rate through relief valve. And each terms in right side of equation (2) means heat transfer rate from secondary side of SG, decay heat rate, added heat transfer rate from pressurizer heater, released heat transfer rate through relief valve.

We determined functions for each term on a basis of standard design specifications for APR1400. That is, terms for HPSI pump and charging pump are expressed as constant values with capacity of run-out flow conservatively. Term for relief valve is expressed as a function of pressure to open at a nominal set pressure plus tolerance of 3% and to have a relief capacity of 29337 L/min at 110% of nominal set pressure. The heat transfer rate from secondary side of SG to primary side can be calculated from constitutive equations as follows;

$$\dot{q}=\int_{z=0}^{z=L}d\dot{q}=\sum_{i=1}^{2}\int_{z=0}^{z=v_{SGM}\times t}A_s\cdot h_{overall}\cdot\left[T_\infty-T_z(z)\right] \quad \text{........(5)}$$

Where $T_z(z)$, temperature distribution inside SG tubes along the flow direction is determined by this equation,

$$d\dot{q}=\dot{m}\cdot C_p\cdot dT_z=A_s\cdot h_{overall}\cdot(T_\infty-T_z) \quad \text{......(6)}$$

Because T_z at z=0 is the same as T_{RCS}, Equation (5) and (6) are combined with energy conservation equation. In this energy balancing equation between inside and outside of SG tube, overall heat transfer coefficient is the combination of heat transfer coefficients as follows;

$$\frac{1}{h_{overall}}=\frac{1}{h_{external}}+\frac{t_{solid}}{k_{solid}}+\frac{1}{h_{internal}} \quad \text{..........(7)}$$

In this analysis, conservatively, we assumed external heat transfer coefficient to be infinite value. Dittus-Boelter correlation for internal heat transfer coefficient includes the terms on velocity inside SG tubes. Simulation on flow distribution in reactor coolant system under one RCP operating condition using MARS-KS shows velocities at pipes and components in reactor coolant system as shown in Figure 1. [3]

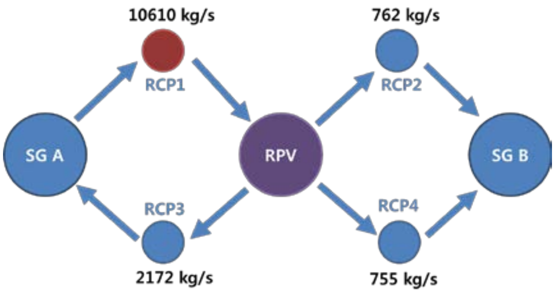
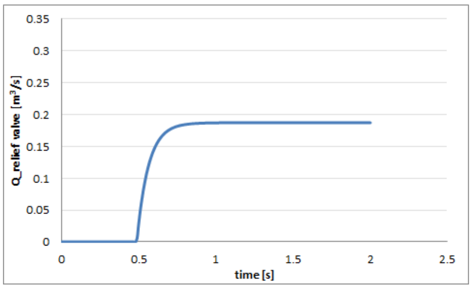


Figure 1 Flow distribution in RCS during on RCP operating

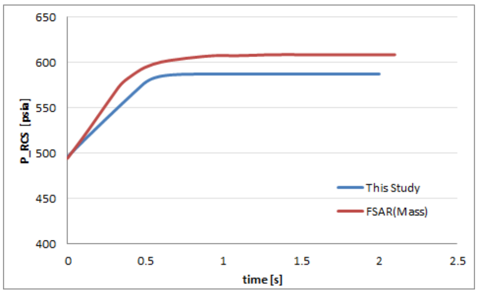
3. Results and Discussions

3.1 Analysis results for mass-addition transients

In this analysis, initial RCS pressure is the same as the pressure assumed in standard safety analysis report for APR1400. Figure 2 shows the results from analysis ~~of~~ for mass addition transients. At about 0.5 seconds after initiating event, the LTOP relief valve starts to open and RCS pressure goes toward constant value. And since about 0.7 seconds RCS pressure almost maintains constant value. In this analysis, the maximum RCS pressure is 586.74 psia. The value is below 620 psia, maximum allowable pressure of LTOP requirement.



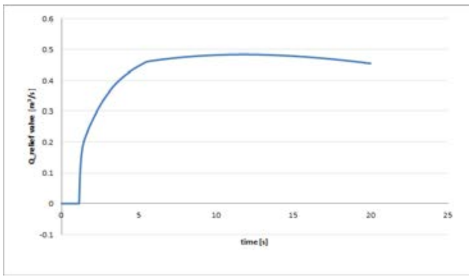
(a) Mass flow rate through LTOP relief valve



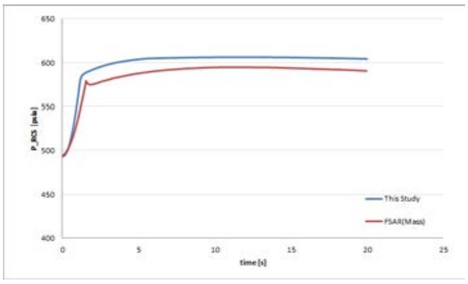
(b) Maximum RCS pressure
Figure 2 Analysis results for mass-addition

3.2 Analysis results for energy-addition transients

In this analysis, initial RCS pressure is also the same as the pressure in standard safety analysis report for APR1400. Figure 3 shows the results from analysis ~~of~~ for energy addition transients. At about 1.15 seconds after initiating event, the LTOP relief valve starts to open and RCS pressure goes toward constant value. And since about 2.0 seconds RCS pressure almost maintains constant value. In this analysis, the maximum RCS pressure is 606.6 psia. The value is lower than 620 psia of maximum allowable pressure ~~for~~ of LTOP requirement. However, according to this result, energy addition transient makes higher RCS peak pressure than mass addition transient in contrast with conclusion in SSAR for APR1400. In further study, detailed review of the conservatism of analysis and the comparison of analysis method is required to explain the difference between this works and analysis in SSAR.



(a) Mass flow rate through LTOP relief valve



(b) Maximum RCS pressure
Figure 3 Analysis results for energy-addition

3. Conclusions

In this study, we evaluated the performance of APR1400 for overpressure transient under cold shutdown status. From the results of analysis of mass addition and energy addition, maximum RCS pressure is maintained lower than maximum allowable pressure for LTOP required in ASME code. Therefore, overpressure protection system of RCS for APR1400 meets the regulation requirements and was enough to perform the function of low temperature overpressure protection.

REFERENCES

[1] ASME Section III, 2000
[2] APR1400 Standard Safety Analysis Report, KHNP, 2014
[3] MARS-KS Manual