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ScienceDirect
Nuclear Science and Techniques, Vol.18, No.2 (2007) 123–128
NUCLEAR SCIENCE AND TECHNIQUES

Analysis of hot leg natural circulation under station blackout severe accident

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Abstract Under severe accidents, natural circulation flows are important to influence the accident progression and result in a pressurized water reactor (PWR). In a station blackout accident with no recovery of steam generator (SG) auxiliary feedwater (TMLB' severe accident scenario), the hot leg countercurrent natural circulation flow is analyzed by using a severe-accident code, to better understand its potential impacts on the creep-rupture timing among the surge line, the hot leg, and SG tubes. The results show that the natural circulation may delay the failure time of the hot leg. The recirculation ratio and the hot mixing factor are also calculated and discussed.

Keywords: Severe accident, TMLB' accident, Natural circulation, Hot leg countercurrent flow
CLC number TL364+.4

1 Introduction

Severe accident natural circulation flows are found to be important to influence the accident progression in a pressurized water reactor (PWR), because energy is transferred from the core to other regions of the reactor coolant system (RCS), to slow the core heatup by natural circulation.[1] There are three main natural circulation flows during severe accidents: in-vessel, hot leg, and flow through the coolant loops. In a hypothetical station blackout accident with no recovery of steam generator (SG) auxiliary feedwater (TMLB'), the coolant system components, hot leg, pressurizer surge line, and SG tubes are exposed to high pressure and high-temperature gas during natural steam circulation cooling. The hot leg, the surge line, or SG tubes can be threatened by creep rupture, prior to vessel lower head failure.[2] If the SG tubes fail first, it results in a containment bypass, with radioactive materials being released into the environment, thus integrity of the steam generator tube is a critical safety issue. On the other hand, when the hot leg or the surge line fails first, the reactor coolant system would depressurize into the containment. If the failure occurs early enough or is large enough, the RCS pressure at the time of vessel failure may be low enough to avoid a high-pressure melting ejection, thus mitigating the effects of direct containment heating (DCH).[3] Therefore, it is significant to analyze the natural circulation flows for severe accident management.

The MAAP severe-accident code is used herein to analyze the hot leg natural circulation phenomenon under the TMLB' accident and its potential impacts on the related creep-rupture timing among the surge line, the hot leg, and SG tubes.

2 Analysis methodology

2.1 Plant model

The MAAP code is an integral system analysis computer code that simulates light water reactor system response to accident initiation events. The referenced plant is a three-loop pressurized water reactor (PWR) with U-tube steam generators. The reactor coolant system is modeled with a reactor vessel, active core region and two reactor coolant loops - the broken and unbroken loops, as illustrated in Fig.1. The broken loop models a single hot leg, steam generator, inter-

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Received date: 2006-07-25

mediate leg, reactor coolant pump, and cold leg. Additionally, the pressurizer is located on the broken loop hot leg. The unbroken loop combines the remaining two reactor coolant loops and steam generators. The core region is modeled with seven radial fuel channels, plus one bypass region, 13 axial active fuel nodes and two non-fuel nodes below the active fuel's bottom and one non-fuel node above the active fuel's top. Considering the TMLB' accident, the safety features and the containment need not be integrated in the plant model.

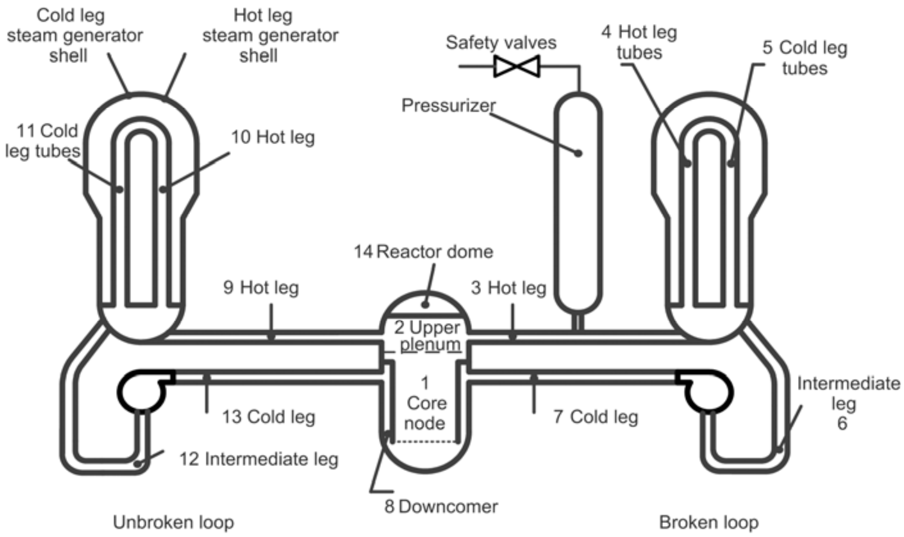

Fig.1 The RCS nodalization.

2.2 Hot leg natural circulation flow model

Three natural circulation flows are important during a high-pressure boiloff transient, such as, the TMLB' sequence: in-vessel, hot leg countercurrent flow, and the flow through the coolant loops. The coolant loop flow occurs following the reactor coolant pumps (RCPs) coastdown early in the transient, and heat is removed from the RCS by the steam generators. In-vessel natural circulation occurs when the core heatup begins and the active core uncovers. It is the result of vapor being heated in the core and cooled in the upper plenum. Because the center part of the core is at a higher power than the periphery, the superheated steam there is hotter and less dense, and a radial density gradient is established. The denser vapor in the outer part of the core tends to flow toward the center, replacing the hot vapor that rises into the upper plenum. This vapor plume rises to the top of the upper plenum, where it is turned outward to the core barrel, and then back down into the periphery of the core.

The hot leg natural circulation is a countercurrent flow in the hot leg, with hotter vapor flowing from the reactor vessel to the steam generator along the top of the pipe, while cooler vapor returns to the vessel along the bottom of the pipe. As illustrated in Fig.2, superheated vapor (m_1) enters the top of the hot leg, displacing saturated vapor, which then flows back to the reactor vessel along the bottom of the hot leg (m_2). After the hotter vapor enters the steam generator inlet plenum, it enters some of the steam generator tubes (m_3), displacing the cooler steam that was in the tubes. The displaced vapor enters the outlet plenum, then reenters other SG tubes (m_4), forcing vapor into the inlet plenum. A density gradient is thus established between tubes. This density gradient then pulls more hot vapor into tubes, displacing the additional cooler steam. The process continues until a steady flow is established.

As shown, a positive temperature difference, T_{up}-T_h, between the hot leg and the SG inlet plenum gives rise to the countercurrent flow, W_{HL}, out to and back from the SG. A difference in the SG inlet and outlet plenum temperatures, T_h and T_c, respectively, gives rise to a flow, W_{SG}, which flows out, to the outlet plenum, through the "out" tubes, and returns to the inlet plenum through the "back" tubes. Considering the flow steams shown in Fig.2, a quasi-steady experimental model of the total countercurrent flow in the hot leg is formulated herein[4]:

$$W_{\mathrm{HL}} = C_{\mathrm{FC}} \rho_{\mathrm{up}} \sqrt{g\beta \left| T_{\mathrm{up}} - T_{\mathrm{h}} \right| D_{\mathrm{HL}}^{5}} \qquad (1)$$

where W_{HL} = total flowrate in the hot leg, $W_{\mathrm{HL}} = m_1 - m_2$, kg•s^{-1}; g = acceleration of gravity, m•s^{-2}; β = coefficient of thermal expansion, K^{-1}; D_{HL} = diameter of hot leg, m; ρ_{up} = density in the upper plenum of the reactor vessel, kg•m^{-3}; T_{up} = temperature in the upper plenum of the reactor vessel, K; T_{h} = temperature of the gas in the SG inlet plenum, K; and C_{FC} = flow correlation coefficient.

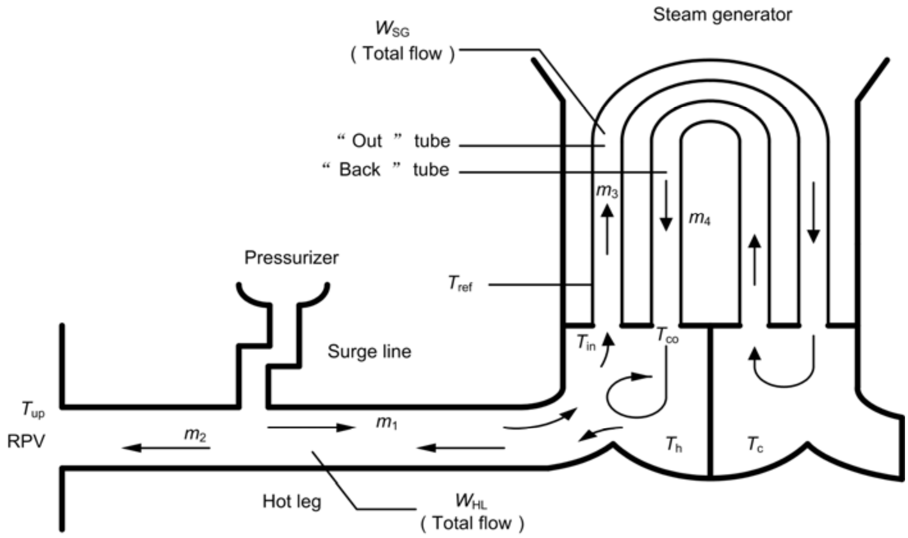

Fig. 2 Hot leg natural circulation.

The natural convection in the steam generator is driven by density differences caused by cooling in the U-tubes. The momentum balance across the "out" and "back" tubes may be written as:

$$\Delta P = \int_L \rho g \mathrm{d}x - \frac{1}{\rho_0} \left(\frac{4W_{\mathrm{SG}}}{\pi D_{\mathrm{tu}}^2} \right)^2 \left(2C_{\mathrm{f}} \frac{L}{D_{\mathrm{tu}}} + \frac{K}{2} - \frac{\Delta\rho}{\rho_0} \right) \qquad (2)$$

where W_{SG} = total flowrate in the SG tubes, $W_{\mathrm{SG}} = m_3 - m_4$, kg•s^{-1}; C_{f} = friction factor; L = length of the tube, m; D_{tu} = internal diameter of the tube, m; ρ = fluid density, kg•m^{-3}; ρ_0 = initial fluid density, kg•m^{-3}; $\Delta\rho$ = fluid density difference between the "out" and "back" tubes, kg•m^{-3}; and K = loss coefficient on account of expansion.

And the temperature of fluid in the tube, as a function of distance x down the tube, is given by

$$T(x) = T_{\mathrm{ref}} + (T_{\mathrm{in}} - T_{\mathrm{ref}}) \exp\left(-\frac{h \cdot A \cdot x}{W C_{\mathrm{p}} L} \right) \qquad (3)$$

where h = overall heat transfer coefficient between the fluid in the tubes and the reference environment, W• m^{-2}•K^{-1}; A = surface area of the tube, m^2; W = flowrate through the tubes, kg•s^{-1}; C_{p} = specific heat of the fluid, J• kg^{-1}•K^{-1}; T_{in} = inlet fluid temperature, K; and T_{ref} = heat sink temperature, K.

So, the temperature of the fluid existing in the steam generator outlet tubes, T_{c}, by analogy with the above equation may be written as:

$$T_{\mathrm{c}} = T_{\mathrm{sec}} + (T_{\mathrm{h}} - T_{\mathrm{sec}}) \exp\left(-\frac{h_{\mathrm{out}} \cdot A \cdot F_{\mathrm{aout}}}{W_{\mathrm{SG}} C_{\mathrm{pgh}}} \right) \qquad (4)$$

where T_{sec} = secondary side temperature, K; T_{h} = inlet vapor temperature of the "out" tubes, K; h_{out} = overall heat transfer coefficient between the outlet tubes and the secondary tubes, W• m^{-2}•K^{-1}; F_{aout} = fraction of tubes carrying the fluid out of the SG inlet plenum; and C_{pgh} = specific heat of the vapor at T_{h}, J• kg^{-1}•K^{-1}.

3 Calculation results and analysis

3.1 Countercurrent natural circulation phenomenon

To analyze the hot leg countercurrent natural circulation phenomenon, the recirculation ratio f and the hot mixing factor r are defined here. "The recirculation ratio" is defined as the flowrate along the bottom of the hot leg from the SG inlet plenum back to the vessel, divided by the steam flowrate at the top of the hot leg from the vessel to the SG inlet plenum. There, the larger the recirculation ratio f is, the more countercurrent natural circulation occurs in the hot leg. “The hot mixing factor” is defined as the flowrate from the SG inlet plenum into the SG tubes divided by the steam flowrate at the top of the hot leg from the vessel to the SG inlet plenum, and a larger hot mixing factor r indicates more mixing in the SG inlet plenum and better tube cooling. As shown in Fig.2, they are expressed as follows:

$$f=\frac{m_2}{m_1} \tag{5}$$

$$r=\frac{m_3}{m_1} \tag{6}$$

As illustrated in Fig.3, during the TMLB’ accident, the countercurrent natural circulation occurs at about 8,500 s. Initially, the flowrate in the hot leg and the SG tubes both increase quickly, and the hot leg natural circulation flowrate is about three times as small as the flowrate in the SG tubes. Then the flow begins to decrease slowly at ~9,000 s, and after 12,500 s, the natural circulation becomes weak and keeps it at a related steady state. Correspondingly, the recirculation ratio and the hot mixing factor are shown in Fig.4. The recirculation ratio f is close to 0.81, and the hot mixing factor r is between 0.95 and 1.4. Table 1 shows the results from a U.S Nuclear Regulatory Commission (NRC) analysis,[5] the 1/7 scale steam generator inlet plenum mixing experiment,[6] the CFD calculation[6,7], and the Purdue University analysis with the MELCOR severe-accident code.[8] The recirculation ratio here is similar to the others. However, the hot mixing factor is smaller than the others. The first and the most important reason is that the TMLB’ accident progression is different because the core power and the reactor coolant system are distinguished from the other analyzed plants or experiments. Second, the main steam safe valves here are operated automatically according to the set-point pressure, but the valves of the steam generator are stuck in the referenced analysis or experiments. The main steam safe valves’ opening depressurizes the secondary system and accelerates the flow in the secondary side, thus the hot mixing factor would be larger. Third, the fraction of tubes carrying fluid out of the SG inlet plenum (F_{aout}, in Eq.(4)) in the calculation model is experimentally set to 0.3, which means only 30% tubes carry vapor flowing along the “out” tubes. But this value might be smaller than the real value.

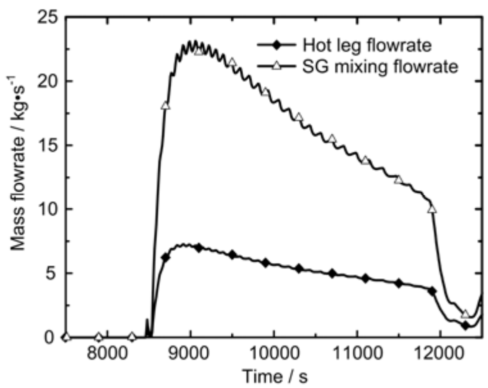

Fig.3 Natural circulation mass flowrate.

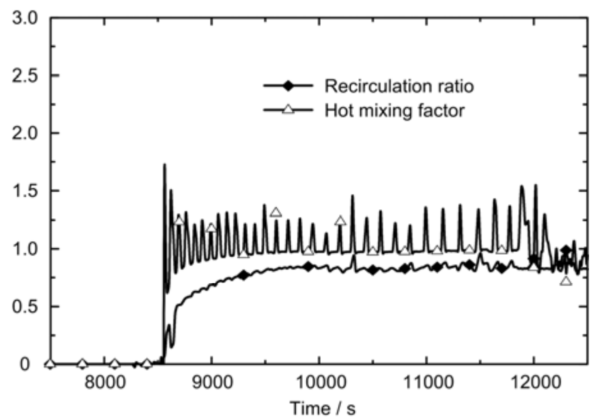

Fig.4 The recirculation ratio and the hot mixing factor.

Table 1 Natural circulation parameters from different sources

Parameter	NRC analysis[5]	Experiment (1/7 scale)[6]	CFD calculation (1/7 scale)[6]	CFD calculation (full scale)[7]	Purdue University analysis[8]	This analysis
Recirculation ratio, f	0.87	0.85	0.81	0.81	0.81	0.81
Hot mixing factor, r	1.9	2.0	2.0	2.7	2.7	0.95~1.40

3.2 Sensitivity analysis of F_{aout}

The Westinghouse 1/7-scale steam generator inlet plenum mixing experiment observed that the values of F_{aout} yielded between 0.2 and 0.45 given in Ref.[6]. In MAAP, a value of 0.3 resulted in the best overall agreement between the model and the experimental data. However, it is not clear which valve in a reactor during an accident would be more similar to the experimental conditions, and a sensitivity analysis needs to be carried out to examine the influence on the hot leg natural flow for the specific plant. According to the experimental observation, values of 0.0, 0.1, 0.2, 0.3, 0.4, and 0.5 are used in the sensitivity analysis here.

Figs.5 and 6 show the sensitivity analysis results of the mass flowrate during the countercurrent flow in the hot leg and SG tubes, respectively. The countercurrent flows occur similarly, unless the F_{aout} value is set to zero to force the flow off. The larger the value of F_{aout}, the more the flowrate occurs in the hot leg and SG tubes. However, this kind of difference becomes smaller, particularly when F_{aout} varies 0.3~0.5. The recirculation ratio, f, is still close to 0.81, and the hot mixing factor, r, is fluctuated at a certain range, as illustrated in Table 2. Therefore, it is indicated that the fraction of tubes carrying fluid out of the SG inlet plenum, F_{aout}, may have little influence on the hot leg and SG flows, and a value of 0.3~0.5 is appropriate on the basis of experimental observation and sensitivity analysis.

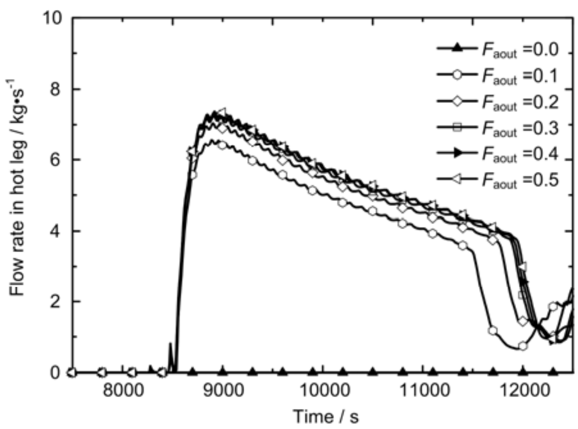

Fig.5 Hot leg flowrate in sensitivity analysis.

Table 2 Sensitivity analysis results of F_{aout}

F_{aout}	Recirculation ratio, f	Hot mixing ractor, r	Average hot mixing factor, $\overline{r}$
0.0	0	0	0
0.1	0.80	0.95~2.7	1.23
0.2	0.81	0.95~1.85	1.22
0.3	0.81	0.95~1.4	1.10
0.4	0.82	0.95~1.4	1.11
0.5	0.82	0.95~1.4	1.12

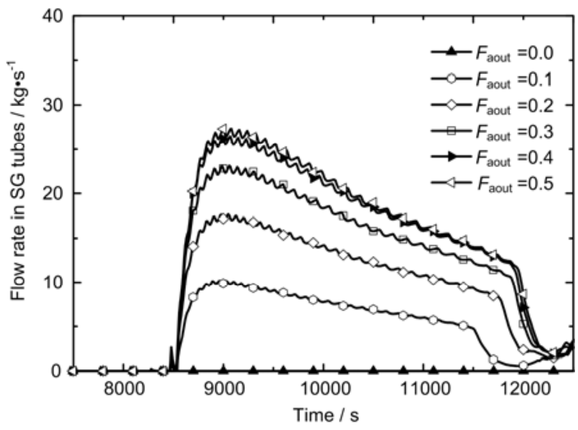

Fig.6 SG flowrate in sensitivity analysis.

3.3 Pressure and temperature history

During the period of hot leg natural circulation, the primary system pressure and the secondary system pressure fluctuate around their safety valves' set-point pressure, respectively, as illustrated in Fig.7. Fig.8 shows the calculations of the heat structure temperature in the hot leg, the surge line, the SG hottest tube, and the SG average tube. The four temperatures start to increase from the beginning of natural circulation. The hot leg temperature increases quicker than the surge line and the SG tube, so the hot leg is most likely to fail by creep rupture. The surge line temperature increases faster than the SG average tube or the hottest tube. Once the hot leg fails, other heat structures' failure risk would be eliminated because the RCS starts to depressurize into the containment. It means that the SG tube integrity could be maintained during station blackout severe accident, which is good for accident mitigation and accident management.

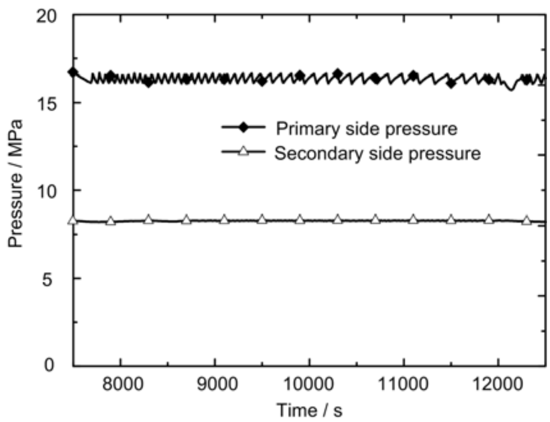

Fig.7 Primary and secondary side pressure.

The Larson-Miller creep rupture failure model is used here to calculate the thermal transient on the heat structures. Heat structure creep failure depends on the pressure and temperature history. In conditions of similar pressure (Fig.7), the variation in the creep failure timing depends principally on the heat structure temperature transient. As shown in Fig 6, the hot leg may have failed by creep rupture at ~11,930 s. Assuming that there is no countercurrent natural circulation in the hot leg, the hot leg creep failure would be earlier (~11,120 s), because its heat structure temperature increases faster (Fig.8). Therefore, the countercurrent natural circulation has potential impacts on the related creep-rupture timing among the surge line, the hot leg, and the SG tubes.

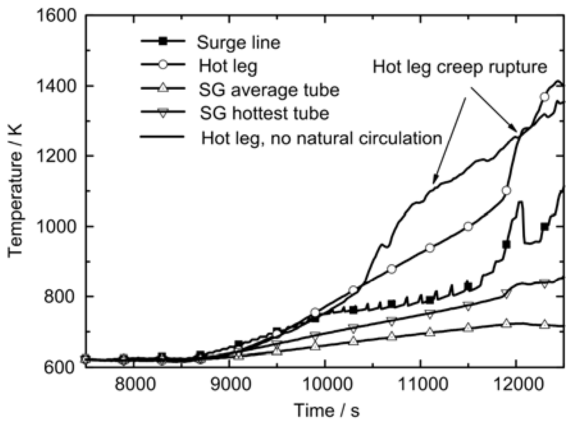

Fig.8 Heat structure temperature history.

4 Conclusions

The hot leg natural circulation might have an influence on the flow patterns and the heat structure cooling in reactor coolant loops. The TMLB' accident is calculated to analyze the natural circulation phenomenon and its potential impacts. A few conclusions can be obtained as follows:

(1) The natural circulation occurs when the hot leg becomes void (~8,500 s), and it is a countercurrent flow. The recirculation ratio f is close to 0.81, and the hot mixing factor r fluctuates between 0.95 and 1.4.

(2) During the calculated TMLB' accident, the hot leg might probably be the first to fail by creep rupture (~11,930 s). Once the hot leg fails, the SG tube failure risk would be eliminated, which is good for accident mitigation and accident management.

(3) The natural circulation increases the steam cooling in the hot leg and steam generator, and delays the creep rupture of the heat structures, which should be considered in severe accident analysis.

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