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Analysis of a Natural Circulation in the Reactor Coolant System Following a High Pressure Severe Accident at APR1400

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1. Introduction

Under a high temperature and pressure condition during a severe accident, hot leg pipes or steam generator tubes could fail due to creep rupture following natural circulation in the Reactor Coolant System (RCS) unless depressurization of the system is performed at a proper time. Natural circulation in the RCS can be a multi-dimensional circulation in the reactor vessel, a partial loop circulation of two-phase flow from the core up to steam generators (SGs), or circulation in the total loop. It can delay the reactor vessel failure time by removing heat from the reactor core.

This natural phenomenon can be hardly simulated with a single flow path model for the hot spots of the RCS, since it cannot deal with the counter-current flow. Thus it may estimate accident progression faster than reality, which may cause troubles for optimized implementation of severe accident management strategies. An earlier damage in the RCS other than the reactor pressure vessel may make subsequent behaviors of hydrogen or fission products in the containment quite different from the single reactor vessel failure. Therefore, a RCS model which treats natural circulation is needed to evaluate the RCS response and the safety depressurization strategy in a best-estimate way.

The aim of this study is to develop a detailed model which allows natural circulation between the reactor vessel and steam generators through hot legs, based on the existing APR1400 RCS model [1]. The station blackout sequence was selected to be the representative high-pressure scenario. Sensitivity study on the effect of node configuration of the upper plenum and addition of cross flow paths from the upper plenum to the hot legs were carried out. This model is described herein and representative calculation results are presented.

2. Modelling of Natural Circulation in the RCS

The existing MELCOR 1.8.5 model for the RCS of APR1400 is shown in Fig. 1. It consists of the reactor core, the reactor vessel and the RCS of two loops with two steam generators, four reactor coolant pumps (RCPs) and a pressurizer. The safety depressurization system is also modeled as two trains. Fig. 2 is a diagram for the interesting part of the RCS in the view point of natural circulation. In this basic model there are two flow paths between the core and the upper plenum, which is different from the SBO-0 case (Fig. 1).

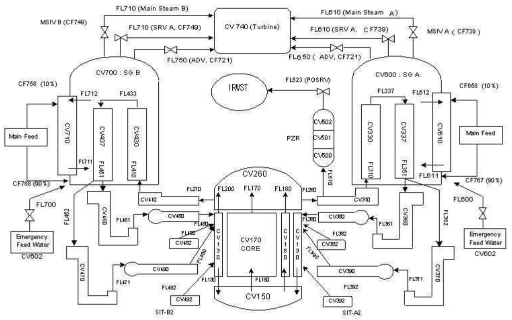


Fig. 1. Nodes and flow paths for APR1400 Reactor Coolant System (SBO-0 case).

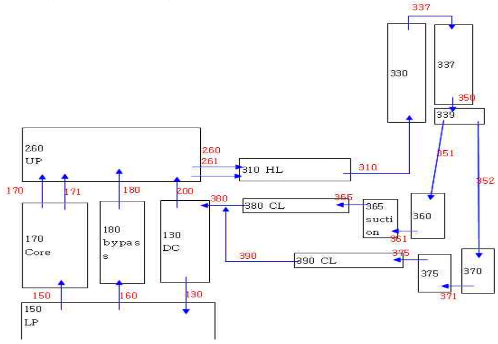


Fig. 2. Basic model for APR1400 Reactor Coolant System (Base case).

When there is an accident and thus two-phase flow is set up in the RCS and the SG can act as both a heat source and a heat sink, the flow directions of steam and water could be reverse. The same phenomenon can be established in the SG tubes. Therefore, the basic model was modified to divide the nodes for the hot legs and the SG tubes into two having the same volumes each. Fig. 3 shows this detailed RCS model.

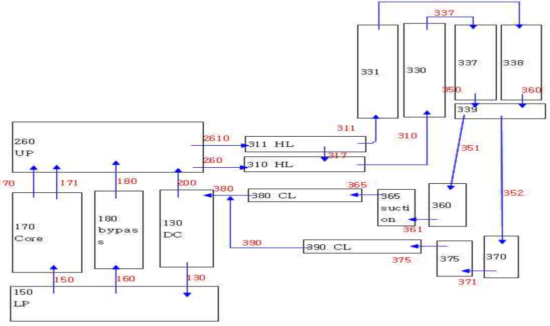


Fig. 3. Detailed RCS model for APR1400 (NAT case).

2. Models for Sensitivity Analysis

In order to analyze the effect of partly detailed models on the RCS response, sensitivity of the upper plenum nodalization and cross flow paths were examined.

2.1 Effect of the Upper Plenum Nodalization

Under the severe accident condition the upper plenum can have a complex two-phase flow pattern with upward and downward directions coexisting. Fig. 4 shows further discretization of the upper plenum of the detailed RCS model.

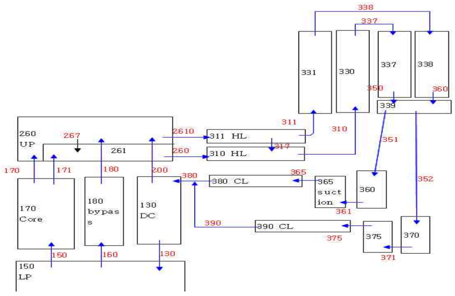


Fig. 4. Detailed RCS model with two upper plenums (NAT2 case).

2.2 Effect of Cross Flow Paths from the Upper Plenum to the Hot Leg

Fig. 5 shows that cross flows between the upper plenum and the hot legs are added to the detailed model described in section 2.1. It seems to be a more realistic model for the RCS.

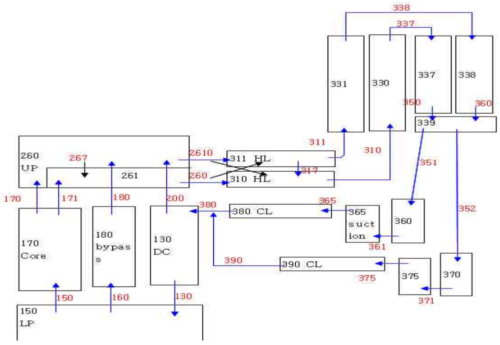
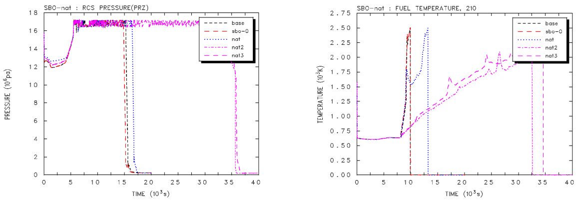


Fig. 5. Detailed RCS model with two upper plenums and cross flows between the upper plenum and the hot legs. (NAT3 case)

3. Analysis Results

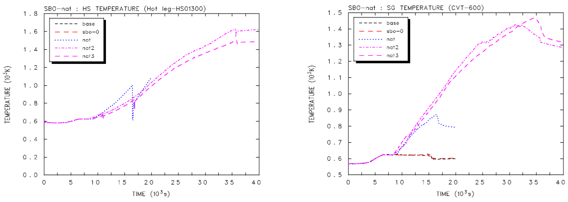
In this section the effect of detailed modeling on the RCS response is described. Fig. 6(a) and Fig. 6(b) show the RCS pressure and fuel temperature estimated for the base and sensitivity cases. Reactor vessel failure time for the NAT2 and NAT3 cases is delayed about 20,000 seconds compared to the SBO-0 and base cases. It can be concluded that the NAT case is not enough for the best-estimate modeling of natural circulation since it has not much improved the single path models.



(a) RCS pressure response (b) Fuel temperature

Fig. 6. Plant reponse.

Fig. 7(a) and Fig. 7(b) show heat structure temperature for RCS hot legs and steam generator tubes. It could not be estimated whether those parts fail or not; however, if failures in the hot legs or SG tubes occur earlier than in the reactor vessel, the RCS pressure response may be different from Fig. 6(a), and a new analysis should be required. Therefore it is needed to develop a new methodology for determination of the failure of the RCS hot legs and SG tubes.



(a) Hot legs (b) SG tubes

Fig. 7. Heat structure temperature for RCS hot legs and steam generator tubes.

4. Conclusions

A detailed RCS model for APR1400 was developed for simulation of natural circulation. It was applied to the analysis of a station blackout sequence as the representative high-pressure scenario. Sensitivity study shows that discretization of the upper plenum and addition of cross flow paths are necessary to enable natural circulation in the RCS. Further work is needed to determine failure of the RCS hot legs and SG tubes.

Acknowledgments

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