Analysis of Post-LOCA Core Inlet Blockage to Evaluate In-vessel Downstream Effect in APR1400

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1. Introduction

During the Operating License (OL) review of SKN Unit 3, an extensive effort has been devoted to evaluate the In-vessel Downstream Effect (IDE) [1~4] based on WCAP-16793-NP Rev.2 [5] proposed as one of the closure option of the Generic Safety Issue (GSI) 191 [6]. In this method, the head loss due to the debris accumulated at the core (dP_{debris}) is determined by the plant specific IDE test adopting the amount of fiber debris to the core determined from the strainer bypass test. Also the available driving head ($dP_{available}$) to supply water to the core for the long term core cooling (LTCC) following the loss-of-coolant accident (LOCA) is calculated to confirm the acceptability of the fuel specific IDE. Meanwhile the cladding thermal response is calculated by the LOCADM code considering all the material on the fuel cladding oxide layer, crud, chemical precipitate, etc.

The method was developed to have a conservatism to cover the uncertainty of analysis and the acceptance is judged by the representative bounding estimation. However, the important safety parameters such as the available driving head need to be confirmed by the plant specific calculation. Also an interaction between the debris induced head loss and the core flow rate needs to be explained because the head loss induced by debris in actual condition may reduce the core inflow rate faster.

To confirm the safety parameters, in this study, thermal-hydraulic response considering the core inlet blockage (CIB) by debris during LTCC process following a double-ended guillotine break of cold leg (CLB), one of hot leg (HLB) and one of intermediate leg (ILB) of the APR1400 were calculated, respectively. MARS-KS 1.3 [7] code has been used. The CIB has been modeled by the closure of valves to the core in exponential manner with time to observe the behavior near the complete blockage.

2. Modeling

2.1 Debris Information

From the licensee's evaluation of IDE based on the strainer bypass test [8], the amount of fiber debris reaching the core was determined as 66 grams per fuel assembly for the HLB. It was based on the assumption that four Safety Injection Pumps (SIP) and two Containment Spray Pumps (CSP) are running, which maximizes the amount of fiber bypassed. Also the fiber debris distribution was assumed to be proportional to the flow rate. Such information was applied to the licensee's IDE test which has a flow rate of the test loop of 77.6 liter/min (lpm) for HLB. The same amount of particle debris as fiber was added to the core to achieve the particle-to-fiber (p/f) ratio of 1 and the maximal amount of chemical debris was introduced according to the protocol of IDE test. The measured head loss due to debris for this condition was 18.7 kPa [8]. The available driving head for HLB considering the boiling within the steam generator (SG) U-tubes was estimated to be 44.8 kPa, which showed a substantial margin between two heads. A similar test has been done for the finer debris of 100 grams, which indicated the maximum head loss of 34.1 kPa. Regarding the CLB, a head loss by debris can be approximated (4.3 kPa) with the flow rate of 11.4 lpm, which was obtained from the available data from the test of 11.4 lpm and the test of 77.6 lpm. The information above was used for the further LTCC calculation.

2.2 System Thermal-hydraulic Model

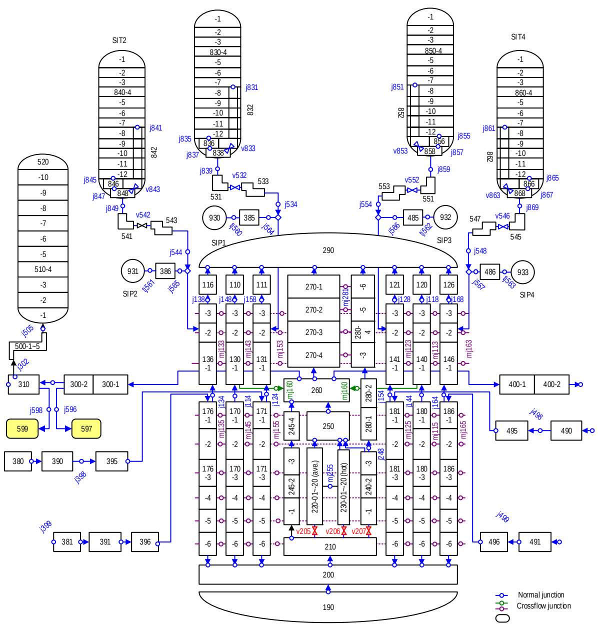

Fig. 1. MARS-KS Nodalization of HLB of APR1400

A typical nodalization of APR1400 for the HLB calculation was presented at Figure 1. All the features of the modeling are the same as the previous study [9] including two-channel downcomer, two-channel core, two-channel Upper Guide Structure (UGS), and four trains of SIS. Safety Injection Tanks (SIT) and the Fluidic Devices (FD) and Standpipe within the SIT were modeled with 'pipe' components specifically. As explained above, operation of four SIP's was assumed and ANS-1973 decay heat model with factor of 1.0 was applied for LTCC analysis.

Servo valve component was used for modeling of core inlet blockage due to debris. Normalized area of the valves (A^*) was specified as a function of time as follows:

$$A^*(t) = A(t)/A_0 = Min[1, \exp\{k_D(t-t_B)\}]$$

where, k_D and t_B mean a debris buildup rate (sec^{-1}) and a time to start to buildup, respectively. It was assumed that k_D =-0.05 and t_B =300 seconds in this analysis, which was more conservative than the case of CIB at 700 sec considered in the original IDE evaluation. The reason for the exponential increase of blockage was to capture a behavior at higher blockage than 95% at which lead a significant increase of pressure drop.

3. Results and Discussion

3.1 Clad Thermal Response

Fig. 2 shows the calculated cladding temperature responses for CLB, HLB and ILB, respectively. As mentioned above, core inlet blockage was initiated from 300 sec and 99.3% closure in 400 sec. The core cladding heatup was found for all the cases a little later than 400 sec.

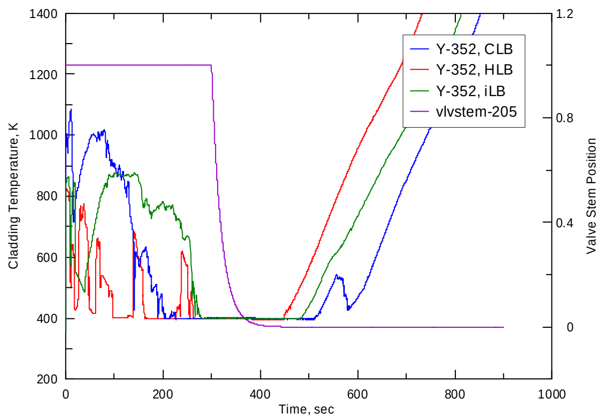

Fig. 2. Comparison of Cladding Temperature for CLB, HLB and ILB

The earliest time to heatup was calculated at the HLB case (448 sec) while the latest one at the CLB case (510 sec). Reason for the difference in core heatup initiation was the difference in flow redistribution within the core under the same blockage condition.

3.2 Blockage Related Parameters

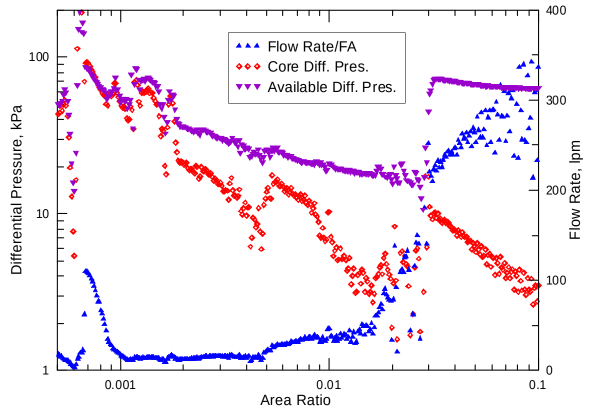

Fig.3. Calculated Flow Rate and Differential Pressures (HLB)

Fig. 3 shows a flow rate per fuel assembly at the core inlet, differential pressure across the valve, and the $dP_{available}$ (dP between the top of SG U-tubes and the bottom of downcomer) for the HLB. Those parameters were plotted as a function of area ratio instead of time. As shown in the figure, the core flow rate is decreased and the inlet dP_{debris} is increased as the valve being closed. However, the trend was not in a simple manner, because of the complex interaction of two-phase flow in the core. At the 77.6 lpm (IDE test condition), dP_{debris} was 3 kPa and the $dP_{available}$ was 20 kPa. When dP_{debris} was 18.7 kPa (the maximum head loss in the test), the core inlet flow rate was 10 lpm and the $dP_{available}$ was 25 kPa. Therefore, it can be clearly stated that the core flow can be maintained under the worst CIB condition representing the maximum debris ingestion. Even at the complete blockage condition (99.9 % blockage at 480 sec), the calculated $dP_{available}$ was 68.7 kPa which was higher than the 44 kPa (predicted by WCAP). The result shows a significant water head was available in the SG U tube.

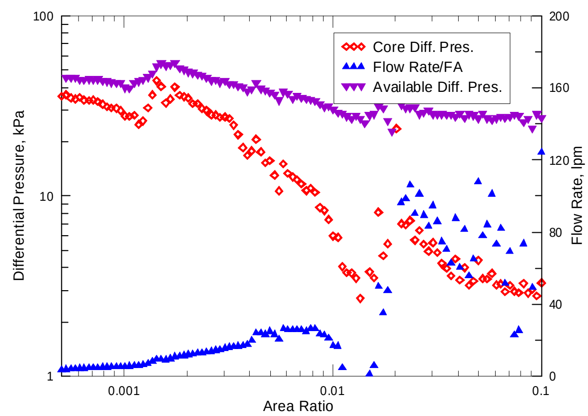

Fig. 4. Calculated Flow Rate and Differential Pressures (ILB)

Regarding the CLB and ILB, almost the same result as the HLB can be obtained. Fig. 4 shows the same parameters calculated from the ILB case. Although the $dP_{available}$ from the WCAP method was not compared, one can find the $dP_{available}$ is always higher than the dP_{debris} whatever the level of blockage is involved.

3. Concluding Remarks

To understand the effect of core inlet blockage (CIB) during a long term core cooling (LTCC) phase following a loss-of-coolant accident (LOCA) in the light of in-vessel downstream effect (IDE) of Generic Safety Issue (GSI) 191, double-ended guillotine break of hot leg (HLB), one of cold leg (CLB) and one of intermediate leg (ILB) were calculated, respectively. And the important safety parameters such as the available driving head and the head loss due to debris were calculated using MARS-KS code and discussed in comparison with the WCAP method. As a result, a little delayed heatup behavior of the fuel cladding was found for all the cases, which due to the redistribution of flow within the core after blockage. The available driving head was always higher than the head loss due to the debris. Additionally, it can be stated that the current modeling scheme adopting valve closure in exponential manner was effective to capture the specific behavior at the range to the completely blocked state.

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