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Long-term cooling analysis considering in-vessel downstream effect for APR-1400 using MARS-KS a thermal hydraulic code

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1. Introduction

Several accidents at nuclear power plants (NPP) have led to the radioactive inventory spill-over in the containment. Recovery from these accidents requires continuous long-term cooling to remove the decay heat. To achieve this, the coolant that is collected in the containment sump is recirculated. During recirculation, fibrous debris may block the sump strainers and reduce the heat removal capacity of the recirculation cooling system, this issue is defined as Generic Safety Issue (GSI) -191 by the Nuclear Regulatory Commission of United States (USNRC). However, the debris that has bypassed the strainers, may reach the core inlet and restrict the coolant flow. This debris can also be deposited on the surface of the fuel and decrease its heat transfer capacity. The effects of debris inside the vessel, are referred to as the in-vessel downstream effect.

Different types of research and tests have been conducted by the Pressurized Water Reactor Owners Groups (PWROG) for developing the safety criteria and demonstrating the safety of the NPP. PWROG submitted topical reports to the US regulatory authority [1] which evaluated these reports using its own methodology [2]. In Korea, a test regarding the in-vessel downstream effect has been performed by the Korea Hydro & Nuclear Power Company (KHNP) [3, 4] and the reports have been submitted to the Korea Institute of Nuclear Safety (KINS), the regulatory authority of Korea. KINS has been verifying the test results independently that they meet the safety criteria as defined by USNRC. However, the methodology for reviewing the test reports is still under consideration.

MARS-KS1.3, a thermal hydraulic code [5], has been selected to develop the methodology for evaluation of the test results submitted by KHNP. The two following modeling problems have been identified for using the MARS-KS1.3 code as the test method: the modeling of the pressure drop due to the blockage of debris at the core inlet and modeling of the chemical deposition layer on the fuel surface. The results have been reviewed and compared with the acceptance criteria defined by USNRC for the GSI-191 [1].

2. Methodology

Methods to resolve the safety issue of the in-vessel downstream effect are described in the WCAP-1693-NP Rev2 [1], submitted by PWROG and approved by the US Nuclear Regulatory Commission (USNRC) [1]. In Korea, similar tests were conducted by KHNP. The tests were reviewed and the evaluation methodology was developed using MARS-KS1.3 code.

2.1 Acceptance criteria

Acceptance criteria for the in-vessel downstream effect, as described in the report, are as follows: the cladding temperature during recirculation should not exceed 800 ^{o}F, and the thickness of the deposition layer of debris should be less than 50 mils on any fuel rod [1].

2.2 Hydraulic Modeling

The topical reports submitted by KHNP [3, 4] to KINS demonstrate that the above criteria have been met. These topical reports contain different tests with respect to the location of the break, amount and types of debris that could reach the reactor core. Two break locations were considered: a hot-leg break and a cold-leg break. In hot-leg break, the coolant enters through the direct vessel injection nozzles (DVIs) and passes through the entire core before spilling into the containment building and the amount of debris that reaches the core inlet is significantly large. However, in the cold-leg break, the flow enters the DVIs and spill-out from the cold-leg without entering into the core. The debris that reaches the core inlet in this case is less than the one in hot-leg break. The inventory added in the latter case provides the make-up for the core boil-off inventory only. The two cases hot-leg break and cold-leg break were simulated for APR-1400 in MARS-KS1.3 code. The modeling scheme was chosen from Y.S Bang et al [6].

2.3 Approaches and methods

To achieve the pressure drop for debris for hot-leg and cold-leg break using MARS-KS1.3, a test model was simulated [6]. A single fuel assembly was modeled as a control volume (CV) and numbered 7. A down-comer of the reactor pressure vessel and flow paths was also modeled and numbered as shown in Figure 1. Flows of 77.6 liters per minute (lpm) and 11.4 lpm of a single fuel assembly during recirculation were selected from the topical report [4] for the hot-leg break and cold-leg break, respectively. These flows were obtained using a time-dependent junction (tj-3) as seen in the model shown in Figure 1. To obtain the desired pressure drop, a servo valve was selected because it provides the option of changing the core inlet area to represent an actual debris blockage. A servo valve (CV-17), with a controlled gate area, was introduced between the bottom nozzle and the fuel assembly region to model the pressure drop effect of debris, and was benchmarked with the value of 34 KPa [6] for the hot-leg break and 3.7 KPa [6] for the cold-leg break case. The valve area as a function of time was added to the valve CV-17 in order to obtain the required pressure drop value with the help of the control-variable option in MARS-KS1.3 [5]. Figure 2 shows the area ratio of the valve and Figure 3 shows the simulated pressure drop of 34 KPa and 3.7 KPa for the hot-leg and cold-leg break, respectively. The time for debris ingression is assumed to be 400 sec.

Area ratio (A) = $A(t)/A_o$= MIN $[1, A_N + abs(e^{k(t_b - t)})]$

Where t_b= the time of debris ingression, t = problem time, k = debris deposition rate and A_N is the normalized area for the required pressure drop and was calculated by running a test simulation in MARS-KS1.3.

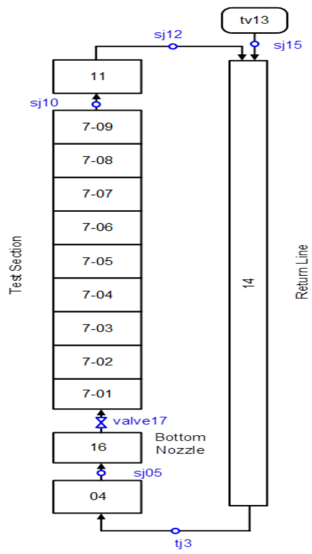

Fig. 1. MARS-KS1.3 model for the test to obtain the pressure drop for debris in cold-leg and hot-leg break

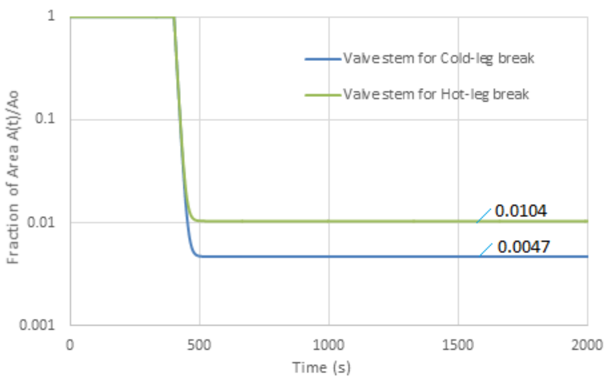

Fig. 2. Valve stem position for the hot-leg and cold-leg break.

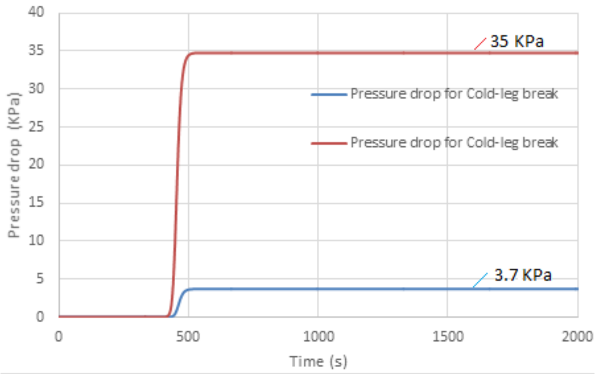

Fig. 3. Debris pressure drop results for hot-leg and cold-leg break

2.4 Modeling for chemical deposition layer

A Fuel assembly is composed of numerous fuel pins. These fuel pins are normally comprised of three layers: pellet, gap and cladding. These layers were modeled as a heat-structure. The modeling of a fourth layer in real-time (when the MARS code is running) is not possible. To solve this problem, the fourth layer was included in the steady state input with a volumetric heat capacity same as that of the cladding and a very high thermal conductivity as shown in Figure 4. To model the fourth layer the gap-conductance, cladding-deformation, and metal water-reaction models were turned-off. The effect of neglecting these model was compensated by decreasing the fuel-clad-gap thickness to 38% of its original value. Figure 5 shows the comparison of the fuel temperature distribution for steady state with and without the models of the gap-conductance, cladding-deformation, and metal water-reaction, respectively.

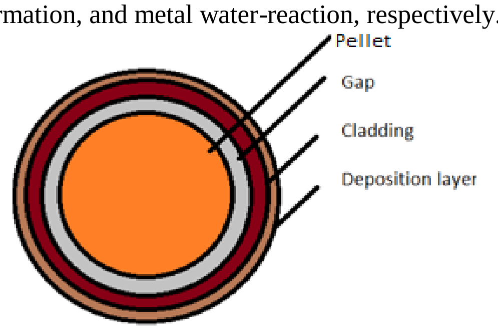

Fig. 4. Modeling of the fourth layer of chemical deposition

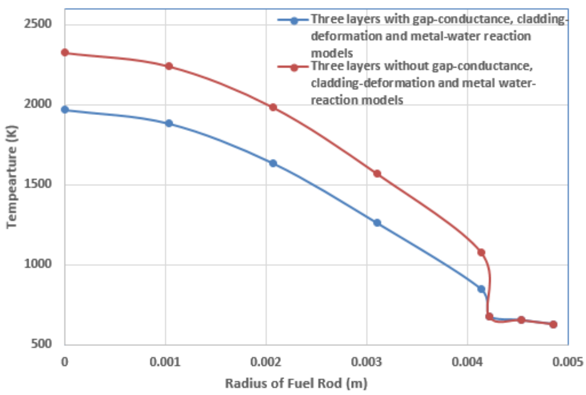

Fig. 5. Temperature distribution with and without gap models in 3 layer case.

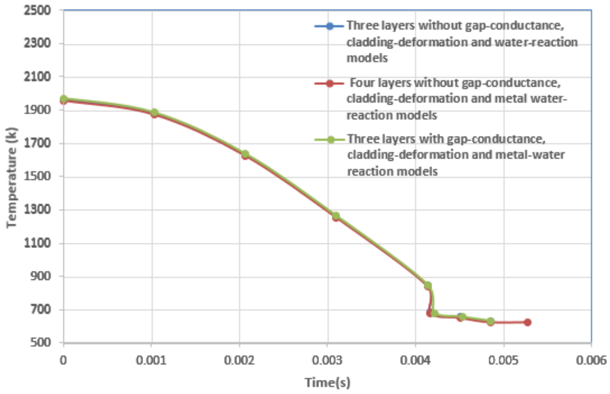

Fig. 6. Temperature distribution with and without gap and deformation models in 3 layer and 4 layer case, after reducing the gap width to 38% of its value.

Fuel temperatures are a function of fuel-clad-gap thickness. The inner-surface cladding temperature and the fuel center-line temperature were calculated as a function of clad-gap-thickness and the thickness was adjusted to have the same temperature distribution as shown in Figure 6.

The 16.69 mils [3] thickness of the fourth layer was chosen from the results of LOCADM analyses for the APR1400 [3] and the value of volumetric heat capacity was given that of cladding as it provides the most accurate value of cladding surface temperature, as compared to the three layer case, in the pre-debris deposition phase. In the post-debris deposition phase (t>400 sec) the value of volumetric heat capacity was chosen based on sensitivity analysis to be 2076 KJ/m^{3}K. Moreover, the value thermal conductivity was calculated by linear interpolation from the data provided in WCAP-16793-NP, Rev2. 20% uncertainty in the value of thermal conductivity (0.5078W/m/K) [0.634824 x (1-0.2)] was considered conservatively. The effect of chemical deposition on the fuel surface was studied and is discussed in the results section.

3. Results and Discussion

As discussed earlier, there are two effects of the in-vessel downstream effect, the first one is the blockage by debris at the core inlet which reduces the coolant flow and the other effect is that of chemical deposition on the surface of the fuel that decreases the heat transfer capability of the fuel.

Figure 7 and Figure 8 show that the available head and the pressure drop due to the effect of debris blockage in cold-leg break and hot-leg break, respectively. These figures clearly indicate that the acceptance criteria defined in section 2.1 has been met. The available head is the differential pressure between the top of the steam generator (SG) u-tubes and the core inlet in the hot-leg break and differential pressure between the top of down-comer and the core inlet in the cold-leg break. There is oscillation in the driving head for the cold-leg break; increases in the driving head are caused by flow reduction due to debris and decreases in the driving head are due to the increase in flow due as a result of previous increase in the driving head.

Figure 9 shows the comparison of the flow per assembly in hot-leg and cold-break. The flow in the cold-leg break is lower than the hot-leg break. The oscillation in the cold-leg break flow is due to the variation in the driving head.

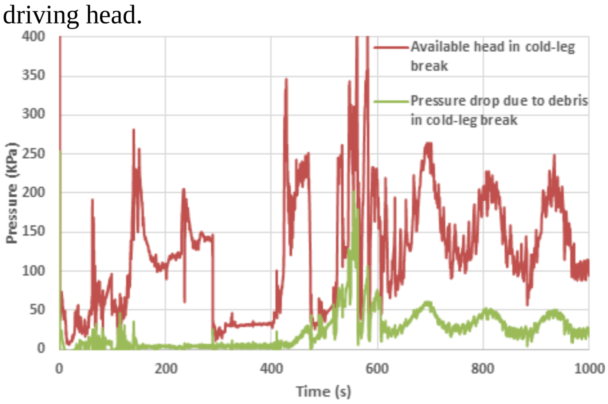

Fig. 7. Comparison of available head and pressure drop due to debris in cold-leg break, debris ingression at t=400 sec.

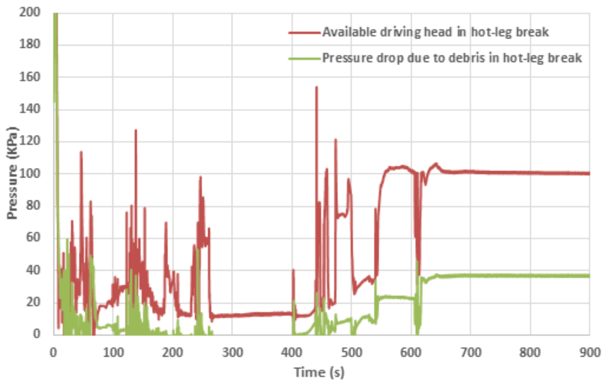

Fig. 8. Comparison of available head and pressure drop due to debris in hot-leg break, debris ingression at t=400 sec.

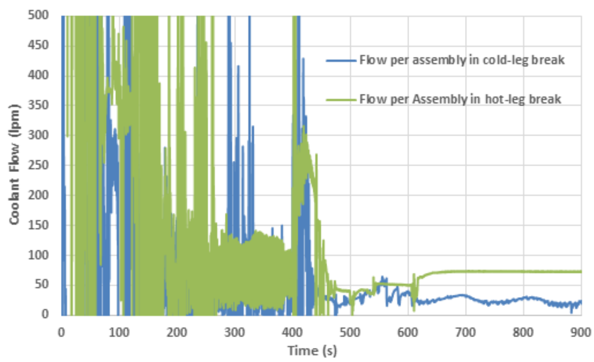

Fig. 9. Flow per assembly in hot-leg and cold-leg break, debris ingression at t=400 sec.

Figure 10 compares the peak cladding temperature for the two cases. According to the reference [4] the debris ingression was at t=700 sec but in this case it was assumed conservatively to be at t=400 sec. There is a certain peak of temperature of about 40 K in the cold-leg break case and 80 K in the hot-leg break case. This peak at t=400 sec depends upon the volumetric heat capacity of the debris deposition layer. The converging response of the temperature is same for different values of volumetric heat capacities and there is a shift of 30 K to 40 K due to the thermal resistance of deposition layer. The value of volumetric heat capacity is important for the initial peak at t=400 sec but not significant for the converged cladding temperature. However, it can be seen that the peak cladding temperature is well below the acceptance criteria defined in section 2.1 (800 °F).

Figure 11 compares the fuel rod radial temperature profiles. It clearly shows that in the case of the debris chemical deposition layer the temperature profile for the fuel rod is less than 30 K above the three-layer case and this shift is due to the thermal resistance of the fourth debris deposition layer.

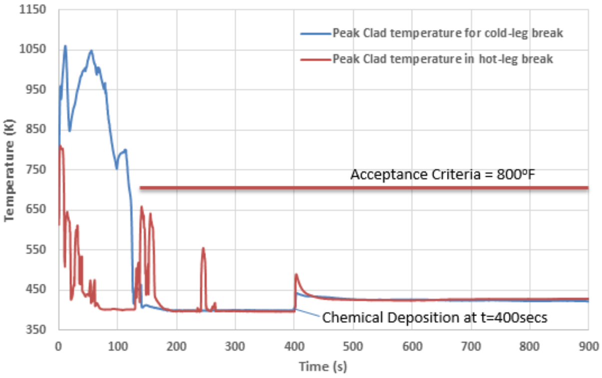

Fig. 10. Peak cladding temperature in hot-leg and cold-leg break, debris ingression at t=400 sec.

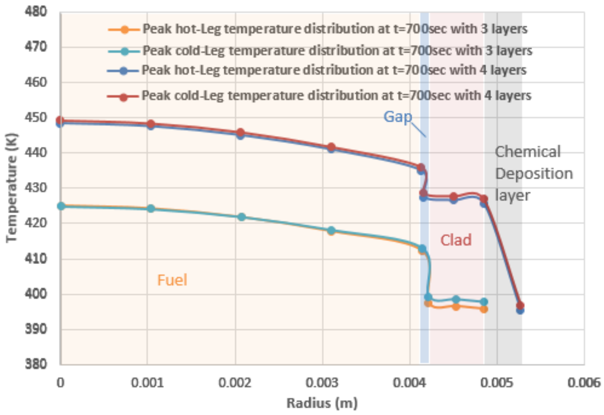

Fig. 11. Peak fuel rod radial temperature profile in hot-leg and cold-leg break, at t=700 sec.

As discussed earlier, this modeling approach has some weakness in regards to the modeling of the fourth layer. At t=400 sec, there are some peaks in the overall results which may be because of the uncertainty in the value of volumetric heat capacity of the deposition layer but after t=600 sec, the results are stable and can be considered credible. Moreover, modeling of the fourth layer also slightly decreases hot-leg and cold-leg temperatures which may not have significant effect.

4. Conclusions

Considering the pressure drop across the active core and the debris deposition on the fuel surface, the calculated peak cladding temperature is well below the acceptance criteria of 800 °F [1]. This clearly indicates that the use of thermal hydraulic code effectively evaluate the safety margin during the long-term cooling analysis considering the in-vessel downstream effect performed by KHNP.

However, there were some conservative assumptions regarding the thickness of the deposition layer, calculation of pressure head available, the volumetric heat capacity, and thermal conductivity of the debris deposition layer. These assumptions should be kept in mind in order to corroborate the current result.

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