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Analysis of Flow Blockage in a KALIMER-600 Subassembly

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1. Introduction

The high heat capacity and the large heat transfer coefficient of a liquid metal enable the compact core design in a liquid metal-cooled reactor (LMR), in which the heat flux from the fuel rods is usually higher than other type of nuclear reactors. Therefore, it is of particular importance to maintain the integrity of the fuel rod configuration and to prevent a local blockage in a subassembly of an LMR. When an obstacle or a blockage is formed in a flow path, the local temperature of the coolant increases at the downstream of the blockage and the integrity of the fuel clad can be threatened.

In the design of an LMR, the consequence of the blockage formation in a fuel assembly is deliberately analyzed with a subchannel analysis code. Since the blockage disturbs the normal flow field it is important to simulate the flow and temperature field correctly in the analysis. When there occurs a blockage in the flow path, the axial flow rate decreases drastically up to a certain distance downstream from the blockage and a re-circulating wake is formed, which induces an increase of the local temperatures of coolant and fuel rod surface.

For the analysis of blockage accident, the KAERI has developed the MATRA-LMR-FB code [1]. This code uses the distributed resistance model (DRM) [2] to describe the sweeping flow formed by the wire-wrap spacers and to model the re-circulation flow after a blockage. The hybrid difference scheme is also adopted to describe the convection in a re-circulating wake region of a low velocity. For the modeling of a porous blockage, a suitable pressure drop model is implemented [3].

The effects of blockages on reactor safety depend on several factors: the size and the thermo-physical properties of blockage, blockage location, fuel pin power, and the coolant velocity in an assembly. Blockages in flow channels will increase the pressure drop and reduce the flow rate. More importantly, the coolant and cladding temperatures in a wake region are generally higher than those without the blockage.

A sudden and large blockage is extremely unlikely in KALIMER-600 [4] design because the inlet flow modules prevent large particles of debris from entering the fuel assemblies. In addition, wire-wrap spacers minimize the possibility of debris trapping in fuel assembly region. Nevertheless, it is still required to understand how blockages can affect the safety because the events may result in a localized boiling or a local clad failure. The design basis event (DBE) for flow blockage analysis is the 6 sub-channels blockage. As beyond DBEs, 24 and 54 sub-channels blockages are considered.

2. Methods of Analysis

The design basis flow blockage events of 6 channel blockage are analyzed with the MATRA-LMR-FB code to evaluate the safety of KALIMER-600 to the flow blockage. A sensitivity study was performed for the possible operation ranges to determine the most conservative condition. Also, sensitivity for the blockage locations of center, middle, and edge was evaluated. The most dominant parameters affecting the analysis results are subassembly inlet coolant temperature, flow rate, and subassembly power. The upper limit of operation range of power is evaluated to be 107 % of the rated power considering the reactor power trip set-point of 111% and the measurement uncertainty of 4%. Similarly, the lower bound of flow rate is determined as 86 % of the rated flow rate and the upper bound of subassembly inlet temperature is 400 ^{o}C.

The driver fuel assembly of KALIMER-600 consists of 271-pins that have the diameter of 8.5 mm, pin pitch of 10.0 mm, and wire-wrap diameter and pitch of 1.4 mm and 193.1 mm. The pins have a total length of 3705.0 mm. The blockage is located axially at 1624.1 mm from the bottom of the assembly with the highest power. The power of a single assembly is 5.53 MW, the inlet flow rate is 25.3 kg/s, and the inlet temperature of sodium is 390.0 ^{o}C. For the analysis of flow blockage, a fuel assembly is modeled into 540 sub-channels, 810 gaps, and 146 axial nodes. Each axial node has 25.4 mm of length which corresponds to 1/8 of wire wrap pitch.

The cases of 24-channel and 54-channel blockages were analyzed assuming the nominal operating conditions. For these large sizes of blockage, the effect of flow reduction was taken into account in the analysis because the reduction of flow is essential in a blocked subassembly. Actually, if a sub-channel is blocked, then the flow rate is reduced by the decrease of flow area and the increase of pressure drop. The increase of peak coolant temperature will be accompanied if the flow reduction is taken into account. The degree of flow reduction is estimated with the pressure balance which takes into account the friction loss and the form loss.

3. Analysis Results

The maximum temperatures of the coolant for the 6-channel blockage were calculated to be 685.3 °C at 88th node for the case of central flow blockage, 684.6 °C at 88th node for the middle flow blockage, and 668.9 °C at 87th node for the edge flow blockage. The temperature in the case of edge blockage is lower than that of other cases because of swirl flow. Figure 1 compares the predicted maximum temperatures for the most conservative case with the nominal case results. It is found that the maximum temperature for the limiting case is higher than the temperature for the nominal case by about 66 °C.

The analyses results for the conservative case show that the peak coolant temperature has enough margin of about 370 °C to the sodium boiling temperature. However, the average subassembly outlet temperature is 657 °C, which exceeds the average core outlet temperature limit. The peak cladding temperature is estimated to be 699.3 °C, therefore, the margin to peak clad safety limit is very small. Thus, it is required to examine the mixing characteristics at core outlet plenum deliberately and the integrity of the structure and the fuel rod clad has to be checked.

The maximum temperature predicted for the 24-channel blockage was 656.0 °C when the flow reduction is not considered. The temperature was calculated to be 668.4 °C with the flow reduction. Also, the maximum temperature for the cases of 54-channel blockages with flow reduction was calculated to be 722.4 °C. The maximum temperatures are occurred at the downstream of blockages due to re-circulating wake. If the beyond-design basis flow blockages are classified into a residual risk of events, the predicted temperatures suggest that there is no significant core damage, therefore, the safety criteria are satisfied even though there occurs some limited cladding failure.

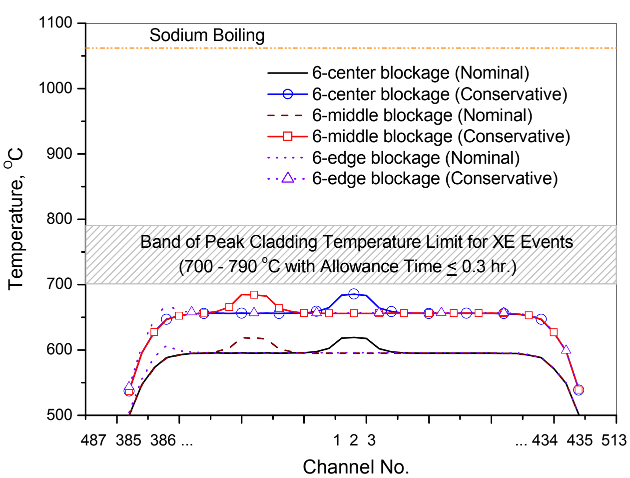

Figure 1. Temperatures for different DBE blocakge locations

4. Conclusion

The design basis flow blockage and the beyond-design basis flow blockage analysis results are summarized in Fig. 2. The analyses results for design basis blockage show that the peak coolant temperature has enough margin to the sodium boiling temperature. However, the average subassembly outlet temperature exceeds the average core outlet temperature limit. The estimated margin of peak cladding temperature to clad safety limit is also very small. Therefore, it is required to examine the mixing characteristics at core outlet plenum and the integrity of the structure deliberately.

For the beyond-design basis flow blockages, the predicted subassembly outlet temperature and the peak coolant temperature are well below the safety criteria, which guarantee no threat to the core heat removal safety function. The peak clad temperature for 54-channel blockage exceeds the fuel clad failure criterion for a XE. However, the general safety criteria are satisfied because a limited cladding failure without significant core damage is allowed for an event of residual risk.

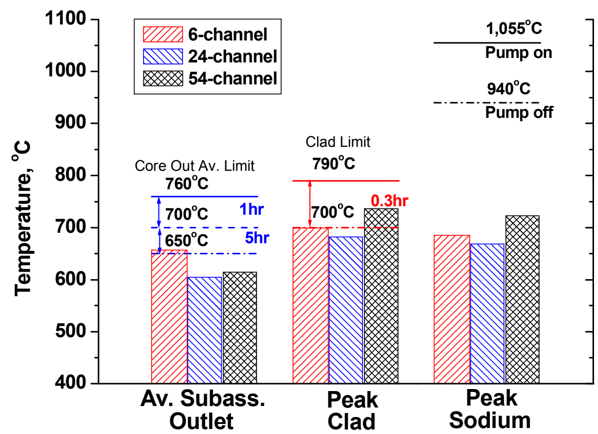

Figure 2. The maximum temperature of coolant according to blockage size

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