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Analysis of Internal Blockage within a Wire-Wrapped Subassembly for Liquid Metal Fast Breeder Reactor

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Abstract

The thermo-hydraulic analysis results for the local internal blockage within a wire-wrapped subassembly are presented. Calculations were performed using the SABRE computer code for the range of blockage positions, sizes, and shapes to investigate the seriousness and detectability of the internal blockage. The magnitude and location of the peak temperatures together with the temperature distribution at subassembly exit were investigated in order to look at the potential for damage within the subassembly, and the possibility of blockage detection. The driver fuel subassembly of KALIMER breeder core was used in this analysis. The analysis result shows that the calculated peak temperatures for 6 subchannel blockage, which is design bases event of KALIMER core, satisfies the acceptance criteria.

1. Introduction

A flow blockage event occurred at the Fermi plant in 1966. A piece of zirconium liner that had broken loose moved into the core inlet region, creating a partial flow blockage that caused fuel damage. The UK and France have experienced flow blockages in experimental facilities. Therefore a flow blockage may happen even though the probability of its occurrence is extremely low.

The flow blockage events are classified into two types, internal and external blockages, depending on their locations. In principle large metallic pieces can be assumed to move with the coolant flow, which have the potential to block a fuel subassembly inlet totally. This is of extremely low probability. External flow blockages at the core outlet may occur due to the complex geometry of internal structures above the core outlet. Events such as pin failures or debris ingress and accumulation could lead to formation of the internal blockage within the subassembly. The internal blockages in the LMFBR subassembly are of particular importance because of tight package of the fuel bundle and the high power density.

To form local blockages in the core regions particles have to be transported into the reactor core. The blockages due to foreign materials can be minimized by advanced design features. Regarding the blockages, emphasis is placed on the local internal and inlet blockages. Fuel clad defects cannot be excluded during reactor operation. If they are not detected and eliminated a certain amount of fuel particles can be swept out and form a blockage inside a fuel element. This mechanism is considered as the most important one for local coolant disturbances inside a subassembly since it can lead to a heat generating blockage.

The issues related to local flow blockages in LMFBR subassemblies are the relative rates of blockage formation and detection, and whether, if formed, a local blockage can progress to a whole core incident, because a local blockage is a necessary precursor to more serious events. Therefore the purpose of flow blockage analysis is to investigate the potential for damage within the subassembly and to investigate the possibility of blockage detection.

In this paper, the results of calculations performed using the SABRE subchannel thermo-hydraulic code for a substantial range of blockages in the driver assemblies are presented. The magnitude and location of the peak temperatures together with their distributions at the fuel bundle exit are investigated in order to look at the potential for damage within the subassembly, and the possibility of blockage detection. The effects of blockage size and position within the fuel pin bundle are investigated.

2. Safety Issue of Flow Blockage

Internal blockage within a subassembly was addressed in the safety assessment in the past LMFBRs because it could potentially have very serious consequences for the reactor as a whole. Many experimental and analytical works have been done to resolve the safety issues related to blockages The present state of knowledge regarding flow blockage mechanisms and consequences seems to be abundant, no many work is in progress in the world. Recently a total flow blockage at the subassembly inlet is of concern for the EFR and PRISM as a limiting event. However, KAERI has a little experience on the experimental and analytical works for flow blockage of LMFBR.

As part of the assessment of reactor safety [1], it is necessary to (1) investigate the causes of the blockages, (2) determine the effects of the blockage (the extent and level of overheating and melting), (3) estimate the rate of damage escalation, and (4) investigate the means of fault detection. As part of the consideration of design purpose, the implications of changes in design parameters on local blockage effects and detection must be considered. The licensing case requires the assignment of flow blockage events to fault categories which are related to the potential radiological release. These events should be analyzed and adequate protection or mitigation justified.

The worst consequences of blockage may be extensive fuel and clad melting. Within the design basis of the LMFBR, the blockage resulting in unacceptable consequences must be precluded by means of the engineering design features and the adequate performance of detection systems. It is very important to know which types of blockages are of most concern to the safety of the subassembly and whether or not any signals would be detected by the reactor instrumentation. In the old LMFBR design concept, thermocouples installed at the subassembly exit detected the blockage before the occurrence of pin failure. After pin failure the Delayed Neutron Detector (DND) could detect the occurrence and ensure reactor safety. The seriousness and detectability of the internal blockage are two major concerns with respect to the LMFBR subassembly design.

In the current LMFBR subassembly design, there is no means (engineering design features) to mitigate the consequences of partial flow blockages, once blockage begin to form within a subassembly. From the view of design concerns, the system should be designed that the probability of blockage formation be very low, if once they happen, the core monitoring system should detect them and core protection system ensure reactor trip as soon as possible before progressing into severe accidents.

3. Subassembly of KALIMER Driver Fuel

The reference core planar layout is shown in Fig. 1. The core utilizes a radially heterogeneous configuration which favors a high breeding ratio. The core planar layout consists of 48 driver fuel assemblies, 18 internal blanket assemblies, 48 radial blanket assemblies, 6 control rods, 1 ultimate shutdown system (USS) assembly self-actuated by a curie point electromagnet, 6 gas expansion modules (GEMs), 48 reflector assemblies, 126 shield assemblies, and 54 in-vessel storages (IVSs). There are no axial

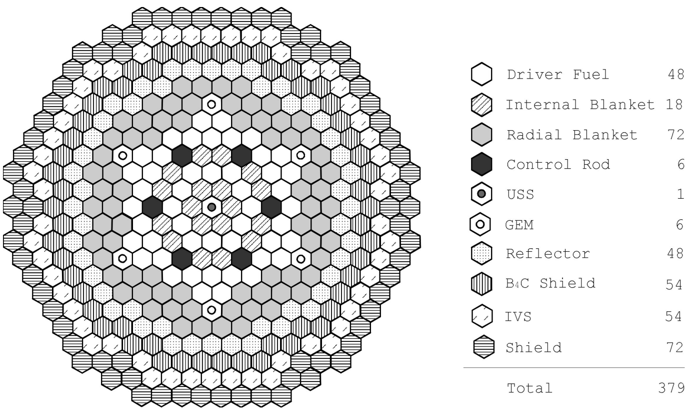

Fig. 1 Layout of KALIMER breeder core

blankets surrounding the core, due to good breeding capacity of metal fuel. The active core height is 120 cm and a radial equivalent diameter (including control rods) is 208 cm. The physically outermost core diameter of all assemblies is 344.7 cm. The fuel form is U-Pu-10%Zr ternary alloy. The driver fuel and blanket have smeared densities of 75 % and 85 %, respectively

The driver fuel subassembly under consideration is located at the center of the core, rated at 7.45 MWth with a flow of 3.8 kg/s giving a coolant temperature rise from 386 °C to 544 °C. The drawings of driver fuel assembly and fuel pin are presented in Fig.2. The driver fuel assembly contains 271 7.4 mm diameter fuel pins held on a 8.9 mm pitch by the wire-wrapped spacer. The fuel element length is 389.3 cm with 111.76 cm lower shielding and 155.0 cm upper gas plenum.

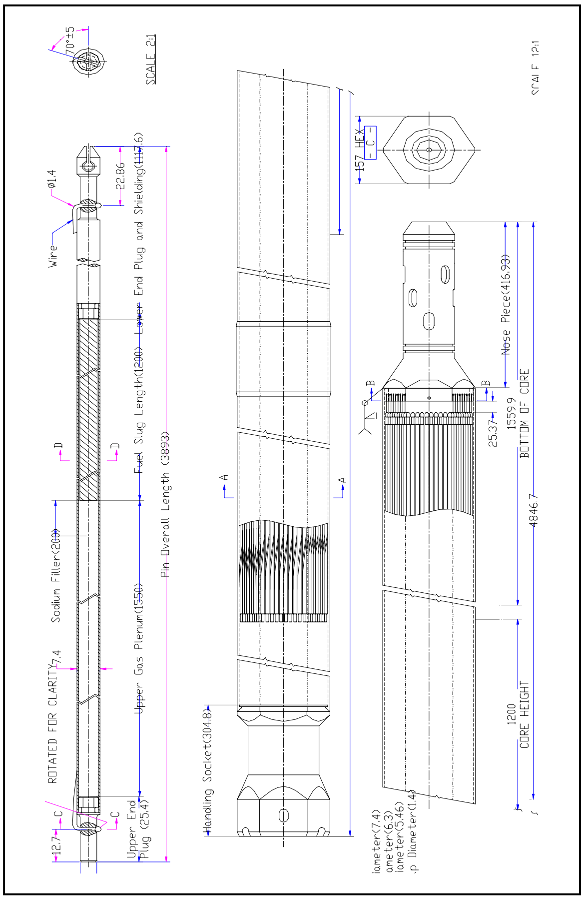

Fig. 2 Driver fuel assembly and fuel pin

The subassembly of fuel driver of LMFBR consists of a cluster of cylindrical fuel pins, surrounded by an outer duct. The coolant flows outside the fuel pins and inside the duct. The fuel pins, which consist of a fuelled core surrounded by an outer tube (called clad), are held apart from one another by a spacer structure. The spacer considered here takes the form of wire wound helically round the fuel pins (called wire-wrap).

4. Flow Blockage Analysis

4.1 SABRE Code

The SABRE [2] code is a general purpose thermo-hydraulic code for calculating the flows and temperatures in rod bundles, using a subchannel representation of the geometry. The subchannel analysis technique gives the most accurate practical representation of the pin bundles. Steady state and transient calculations can be made of both single and two-phase flows. The latest version of the SABRE4b permits the calculation of boiling transients. Both semi-implicit and fully implicit solution methods are available in the code and a vector upwind

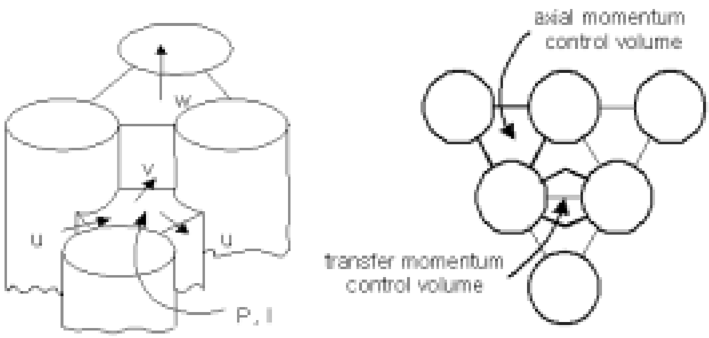

Fig. 3 Nodes and control volumes of SABRE

differencing scheme is included. Pin temperatures are calculated using radial or radial and azimuthal conditions, and heat loss through the wrapper wall is permitted.

The major objective of the code is to provide a calculation tool that can be used for the non-standard configurations that occur in safety analysis. The code has a capability to deal not only with unperturbated fuel pin bundles, but also to deal with distorted geometries which may occur during reactor operation such as rod bowing, and with accident situations in which such events as blockages, coolant boiling and natural convection might occur. The code calculates recirculating wakes behind blockages in rod bundles. SABRE permits the inclusion in the rod bundles of any number of planar blockages which may be specified as either permeable or impermeable.

The geometrical representation in SABRE4 is based on a regular mesh of pins. The code has been designed primarily for use with a triangular array of pins, but may also be used for calculations with square arrays of pins. The main variables are the flow velocity components u, v, and w, the static pressure p, and the energy I, The axial direction is that of z coordinate. The layout of nods and control volumes in triangular geometry are defined as shown in Fig.3. The main nodes (i,j,k) are taken at the centers of the subchannels defined by the surfaces of three surrounding pins and the lines joining their nominal centers. The nominal pin centers lie on a uniform triangular mesh. The velocity nodes are taken at the mid points between the main nodes. For the axial velocity w, the control volume is a section of subchannel, but lying between adjacent main nodes. For the transverse velocities u and v the control volume is taken as the volume bounded by the lines joining the two adjacent nominal pin and subchannel centers, the adjacent pins and the adjacent axial velocity planes.

4.2 Analysis Method

The analyses of internal blockage may require a wide range of spectrum analysis, because blockages may have different shape, size, location and permeability. The effects of blockage size, position within the fuel pin bundle, and porosity have to be investigated. Since there is no guideline and experience for KALIMER blockage analysis, all those variables have to be varied to identify the worst case with respect to peak temperature. For example, the blockage size may varied from single subchannel to 2, 4, 6, 24, etc., and the blockage depth from 1/6 wire wrap lead to 1/3, 1/2, 1, 2, etc. The horizontal locations considered here are only two cases of bundle center and corner.

In addition to the variation of the blockage itself, the sensitivity of analytical models, included in the SABRE code, on the calculation results must be evaluated. Among many analytical models and their coefficients, sensitive ones have to be identified and their effects on the calculation have to be quantified. However, this analysis follows the recommended values presented in the SABRE manual.

The primary important parameters in the blockage calculations are the location and magnitude of the peak temperature and the effects seen at the subassembly outlet. The peak temperature is obviously vital for determining the seriousness of the blockage, and the location of it provides information for purpose of blockage detectability analysis. The peak temperature region may be located in the blockage itself or may appear within a recirculating wake. Since the proposed design for the KALIMER driver assembly use wire wrap to space the pins, the analysis has to encompass the whole bundle if the swirl effects generated by the wire-wraps are to be properly taken into account.

In general for large reactors, the reactivity feedback effects due to fuel heat-up are small, so the assumption of constant heat flux on the fuel pin during an entire blockage transient is reasonable in the analysis in the initial stages of the event (no pin failure and no fuel melting). Therefore the approach of de-coupling of thermal-hydraulic and neutronic calculations can be justified.

The assumptions made in the blockage analyses are as follows. (1) The blockage events are assumed to occur at full-power normal conditions. (2) The primary pumps (EMP) normally operate during the blockage events. (3) The transient analyses are performed with respective to thermal hydraulic concern, the neutronic calculation is not considered. In other words, the heat flux generated in the fuel pin is constant throughout the entire transient, which does not vary due to the reactivity feedback effects in the core. (4) The fuel slug is assumed to contact to the cladding. (5) All geometric data of fuel pin are based on the hot conditions, which take accounts into the thermal expansion effects. (5) The thermal conductivity used is the reduced case in order to account for the uncertainties in the data collected to date and to reflect the fuel's behavior under irradiation. (6) Total 7.45 MWt power of a single driver assembly is axially distributed in cosine shape. The flow rate is 39.8 kg/s and inlet temperature is 386.2 ^{o}C.

The safety objective of the flow blockage in the design bases event is to maintain coolability of the incident subassembly. The coolability will be maintained if extensive clad damage is avoided. Therefore, the acceptance safety criteria [3] used for the bounding events in KALIMER, which includes the characteristics of metallic fuel can be also applicable to the flow blockage analysis.

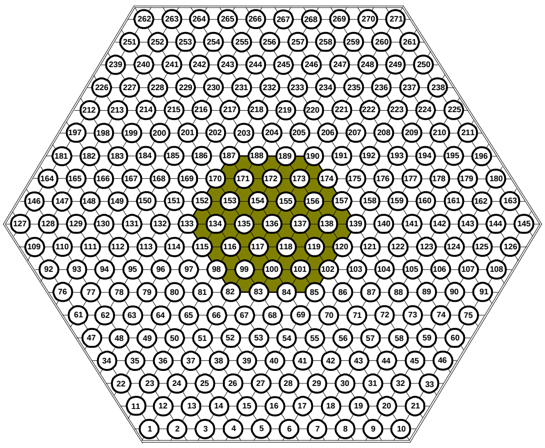

Fig.4 Central 24-subchannel blockage

4.3 Analysis Results

According to the experiments, the shape of blockage within the wire wrapped bundles is known to be long and narrow. Based on the experimental results, the most of blockage considered in the design bases event are for 6 subchannel blockages where all subchannels surrounding a particular pin are blocked. However, no significant temperature rise was calculated by SABRER, 24 subchannel blockage was considered. Figure 4 shows the numbering system of driver fuel assembly for blockage analysis, specially a central 27 subchannel blockage. A whole assembly was evenly divided into 117 meshes in axial direction, and 40 and 21 meshes in x and y direction, respectively. Total 271 pins and 900 subchannels have their unique numbers as shown in ig.4

Figure 5 depicts the velocity vectors at the inlet and mid-plane, and outlet of assembly for steady state condition, in which the swirling effect due to wire-wrap is shown. Figs 6 and 7 are the temperature contours in x-y plane, at the middle and outlet of assembly, for steady state and central 24 subchannel blockage cases, respectively. The axial power shape has its maximum value at K=51 position which is slightly above the middle of assembly. Figure 8 shows the temperature distribution in x-z plane. The highest temperature of 954 K occurs within the blockage itself, which satisfies the safety criteria. The temperature at the assembly exit for 24 central blockage is about 572 K in contrast with 555 K at steady state. The temperature difference at the exit is only 17 K which seems not enough for thermal sensor installed at the top of assembly to detect the abnormality.

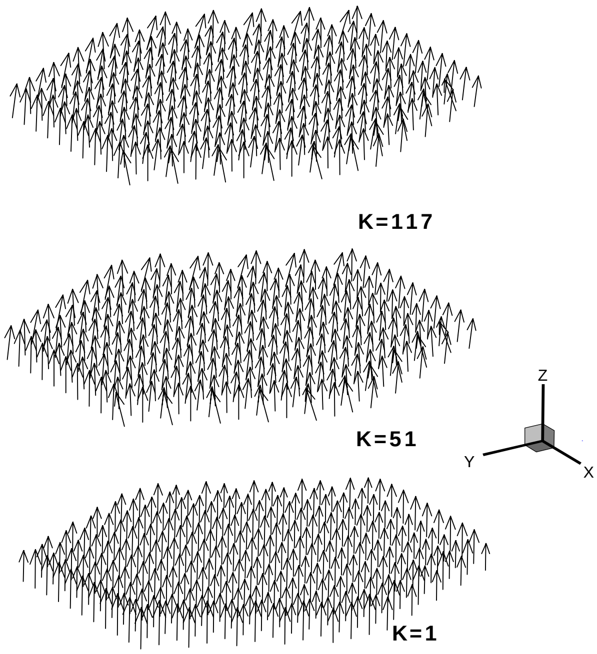

Fig. 5 Velocity vectors at inlet, mid, and outlet location of subassembly

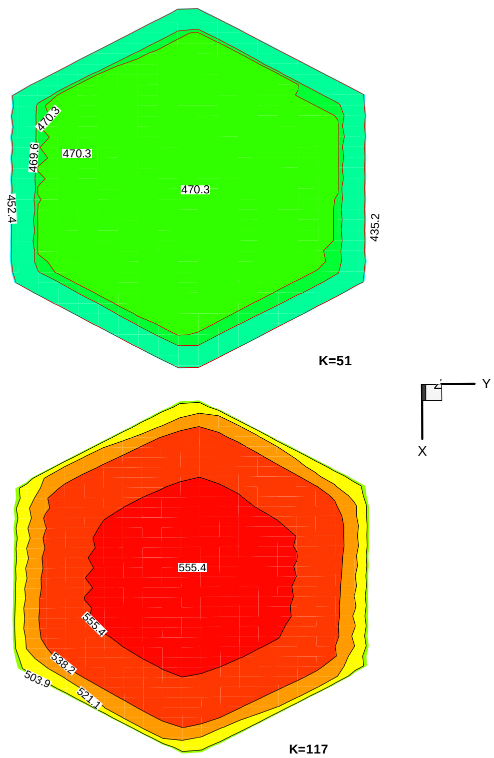

Fig.6 Temperature contour at steady state (K=51, 117)

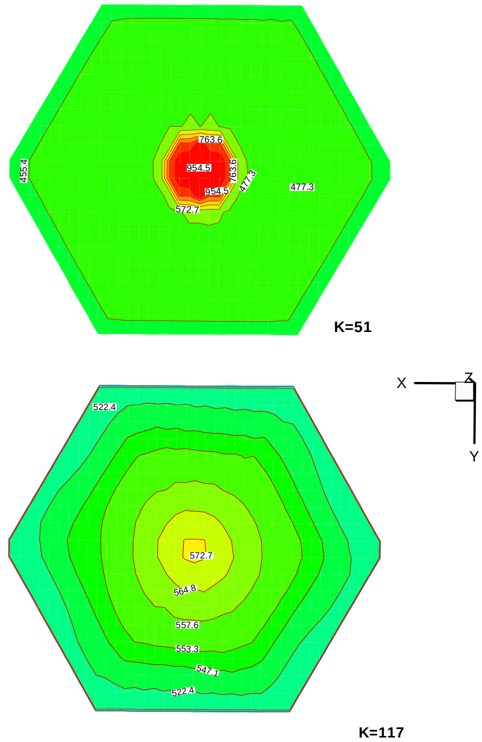

Fig.7 Temperature contour for central 24 subchannel blockage

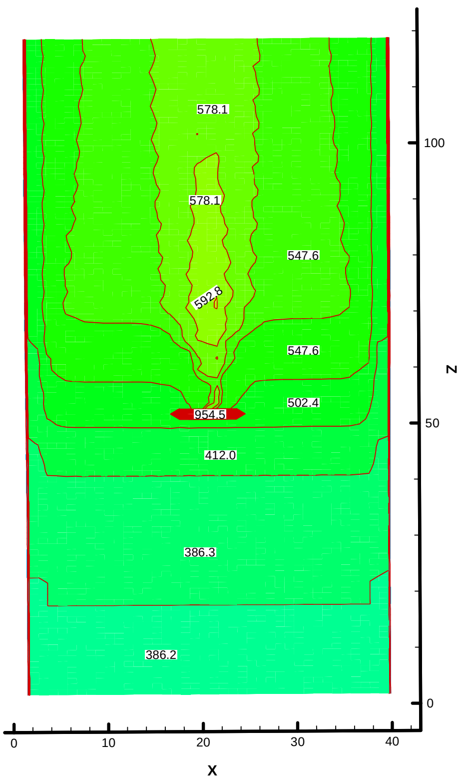

Fig. 8 Temperature contour in x-z plane for central 24 subchannel blockage

Figure 9 is the analysis result of peak temperatures for 6 subchannel blockage cases at central and edge location, respectively. The calculated temperatures are represented as function of blockage depth which is defined as the number of wire lead. For the 6 subchannel blockages, the SABRE calculations indicate that the peak temperatures were found within the blockage themselves in all cases. The peak temperature variation with the blockage position is shown in Fig. 9 where the blockage has no porosity. The temperature rise in any position is insufficient to bring the sodium temperature to the boiling point. It was found that the position

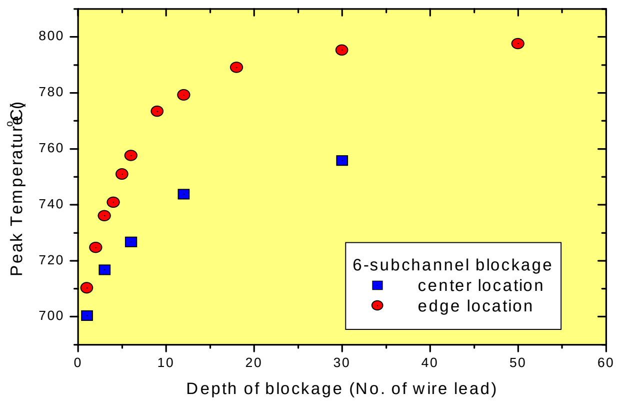

Fig.9 Peak temperatures of 6 subchannel blockages

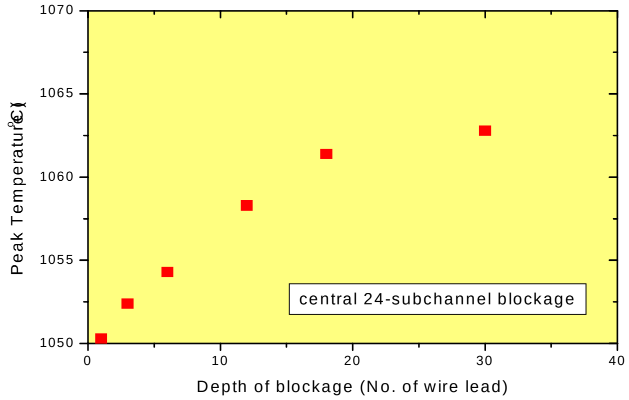

Fig.10 Peak temperatures of 24 subchannel blockages

of the blockage seemed to have little effect on the results unless the blockage was actually adjacent to the wrapper. Calculations of 6 subchannel blockages in six corners of the hexagon show higher temperature rise than central blockage case. These results serve to illustrate the importance of the wire wrap model in the SABRE. The calculated peak temperature for 24 central blockage .exceeds the boiling point as shown in Fig.10

5. Discussion and Conclusion

For the assessment of reactor safety and for the investment protection in the LMFBR, it is necessary to determine the effects of the blockage such as the extent of overheating and melting. This analysis determines not only the blockage parameters of size, shape, and location, but also yields the information necessary for the blockage detection system. The effects of the blockage on the flow rate and temperature rise are used to assess the viability of the detection systems as a means of plant protection required for the important detection parameters before pin failure.

With respect to blockage formation in the LMFBR subassembly, wire-wrapped rod bundles can have certain advantages compared to grid spacing. According to experiments, the radial extension of blockages is substantially limited in the wire-wrapped bundle design, whereas in grid-spaced bundles, a horizontal particle bed with strong radial growth tendency has been found. However the effect of distortion of the wire wrapped bundle during irradiation, and the possibility of wire wrap failure, should also be considered

According to experiments, the formation and growth of a blockage strongly depend on the particle diameter and flow conditions. For the wire-wrapped design it is quite unrealistic to consider the planar blockage which covers the adjoining subchannels in the same axial locations, a six-subchannel blockage surrounding a pin for example. The formation of an impermeable blockage is highly unlikely due to the geometrical relationship between the spacer wire and the pins. Therefore, the resulting blockage should be highly porous.

Obstruction of the coolant flow in subchannel of a subassembly might trigger a chain of fault propagation leading to severe damage of the core. Internal blockage causes high temperatures occurring within the subassembly. The local formation of high temperature regions may be severe if it remains unseen outside of the incident subassembly. In this study 6 subchannel blockages, which is design bases event of KALIMER, did not have a substantial change to the overall coolant mass flow rate through the subassembly, therefore they make little difference to its mixed mean temperature at the subassembly exit. It was found that high temperature region was located in the blockage itself.

The blockages that are not detected result in pin failure. Once the fuel pin fails, the subsequent fission gas release and following fuel liberation release can be clearly detected. As soon as the DND detects the pin failure, the reactor protection system ensures a scram. However, there is no design requirement to mitigate the blockage progress itself. A mitigation of blockage propagation is practically very difficult to implement into the system design because the progress of the blockage can be very rapid.

Acknowledgment

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