RERTR 2015 – 36TH INTERNATIONAL MEETING ON
REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS

OCTOBER 11-14, 2015
THE PLAZA HOTEL
SEOUL, SOUTH KOREA

Damage Propagation of Plate Type Fuel by Flow Blockage Accident of a Research Reactor

Byeonghee Lee and Suki Park
Research Reactor Core Design Division
Korea Atomic Energy Research Institute, Daedeokdaero 989-111, 34057 Daejeon – Korea

ABSTRACT

A fuel damage propagation of research reactor is investigated during a complete blockage of a fuel channel. Individual fuel channels are modeled with conservative assumptions for analyzing the behavior of blocked channel and neighboring channels, and the maximum temperatures are investigated to assess the integrity of fuels. The fuel integrity of neighboring fuel plates are ensured although the fuel plates of blocked channel are damaged by the accident. In addition, direct heat conduction and radiation between the fuel plates are considered as well as the convective heat transfer by coolant. The temperature of neighboring fuel plates increases at the edge where the heat flows into the plate, however, the temperature does not exceed the blistering temperature of fuel, which means the fuels are safe.

1. Introduction

A research reactor with plate type fuels has isolated narrow rectangular cooling channels. When a fuel channel is completely blocked, the cooling capability of blocked channel is lost and the fuels facing the channel (closed channel fuels) can be damaged. The heat generated from the closed channel fuels are then transferred to the neighboring channels, which can cause the damage propagation to next fuels (open channel fuels). Since the closed channel fuels can experience the critical heat flux (CHF) conditions during the accident, a proper CHF correlation need to be implemented in the analysis code.

In this paper, the complete blockage of single flow channel is analyzed for a research reactor with RELAP5/MOD3.3 having newly integrated CHF correlation suitable for the narrow rectangular channel. Also, the convection and radiation from the closed channel fuels to the open channel fuels are analyzed with one dimensional approximation and conservative assumptions. The integrity of the closed channel fuels and the open channel fuels are then estimated from the maximum fuel temperatures of them.

2. Flow Blockage Accident

A flow blockage accident of research reactor occurs by an intrusion of foreign materials or debris into the core, blocking a fuel channel. Since the cooling channels with plate type fuel are isolated from each other, a complete blockage of single fuel channel can cause damage at the closed channel fuels. However, since the reactor parameters such as flow rate or coolant temperature do not change much by the single channel blockage, no prompt reactor trip occurs by those parameters. Instead, once the fuel damages and the radioactive elements are released to the coolant, then the reactor can be tripped by the PCS high radiation or the pool surface high radiation signals of reactor protection system.

A 15 MW pool-type research reactor is selected as a model reactor for the analyses. Since the reactor has semi-closed coolant loop with small openings at the reactor structure with meshes and holes, any foreign materials or debris entering into the core is not probable. Nevertheless, a complete blockage of single flow channel is assumed at the reactor for demonstrate the subsequent event consequences by the accident.

3. RELAP5 analysis with Kaminaga CHF correlation

The complete blockage of single fuel channel is analyzed with RELAP5/MOD3.3. The closed channel fuels can experience a CHF condition during the accident, therefore, an adequate CHF correlation is critical to simulate the fuel temperature and heat flux properly. Since the RELAP5/MOD3.3 does not equip a proper correlation set for narrow rectangular channel of the reactor, Kaminaga CHF correlation is written as a new subroutine and is included in the code. Kaminaga CHF correlation is developed for narrow rectangular channels, and composed of three different equations for upflow, downflow and flooding CHF, respectively [1]. Kaminaga correlation covers the operational conditions and the channel geometries of the research reactor. Considering the correlation uncertainty of 33%, the CHF calculated from Kaminaga correlation is divided by 1.5 in the code.

Figure 1 shows the core model for flow blockage accident analyses. Although the entire reactor system is modeled for the analyses, the flow rate through the core changes negligibly during the accident, therefore the system modeling is not important. The core is modeled with three hot channels, one average channel, and five heat structures dividing heat to the channels. Three hot channels represent the blocked channel and the neighboring two open channels, are conservatively modeled to have 90% of average flow rate of the other fuel channels. Also, the heat structure attached to hot channels generate higher power than that attached to average channels, considering a radial peaking factor and an engineering hot channel factor.

The flow blockage is modeled as a sudden close of valve to the channel, P242, and the heat structures surface to the channel are assumed to be insulated with the accident initiation for conservative analyses. By the insulation assumption at the heat structure surface, the temperatures of closed channel fuels increase above the melting temperature of fuels, which is physically impractical. Above the melting temperature of fuel, the specific heat of the fuel can be assumed either to be constant or to be infinite above the melting point. The constant specific heat assumption predicts the fuel temperature impractically high, but the heat flux from the fuel is realistic. On the other hands, the infinite specific heat assumption predicts the fuel temperature to stay at the melting point, but the heat flux from the fuel is lower than former one because a portion of heat generation is accumulated in the fuel. Since the heat flux from the closed channel fuel manly affects the damage propagation of fuels, the constant specific heat assumption is used for the analyses for more conservative analyses.

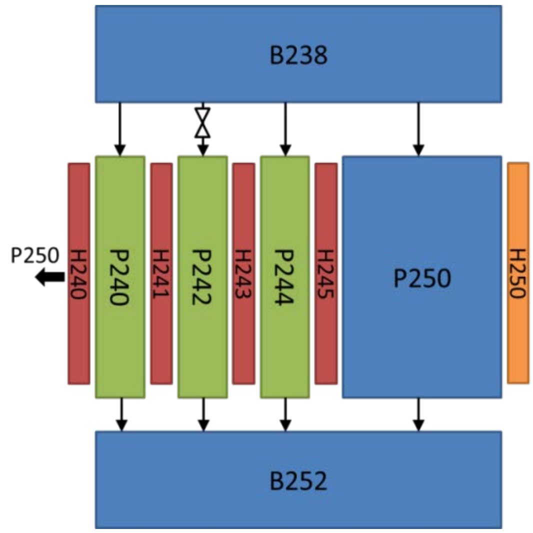


Figure 1. Core model for flow blockage accident

3.1. Closed Channel Fuels

Figure 2 shows the maximum fuel temperature and the heat transfer regime at the surface of closed channel fuels, with respect to the CHF calculation methods of RELAP5/MOD3.3. AECL-UO table is a default method of CHF calculation in RELAP5/MOD3.3, which is based on the database from power plants [2]. AECL-UO tables estimates the CHF to be much higher than that from Kaminaga correlation. The fuel with AECL-UO table does not experience the CHF and remains in a subcooled nucleate boiling regime. On the other hand, the fuel with Kaminaga correlation exceeds the CHF points, shifting to a subcooled film boiling regime. Therefore, the maximum fuel temperature calculated with Kaminaga correlation far exceeds the melting temperature, but that with AECL-UO table is still remains under the melting point. The results show that the integrity of closed channel fuel can be judged differently with respect to the CHF calculation. Since the fuel temperature exceeds the fuel melting temperature of 570^{o}C with Kaminaga CHF correlation, the closed channel fuels are predicted to be damaged.

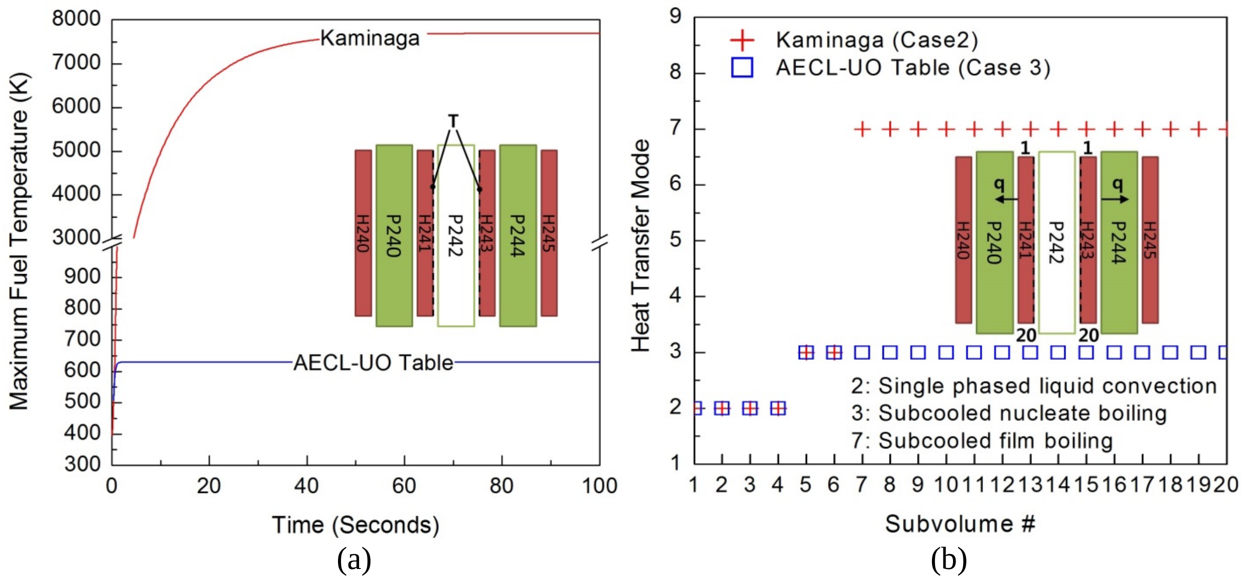


Figure 2. (a) Maximum fuel temperature and (b) heat transfer regimes at the closed channel fuels

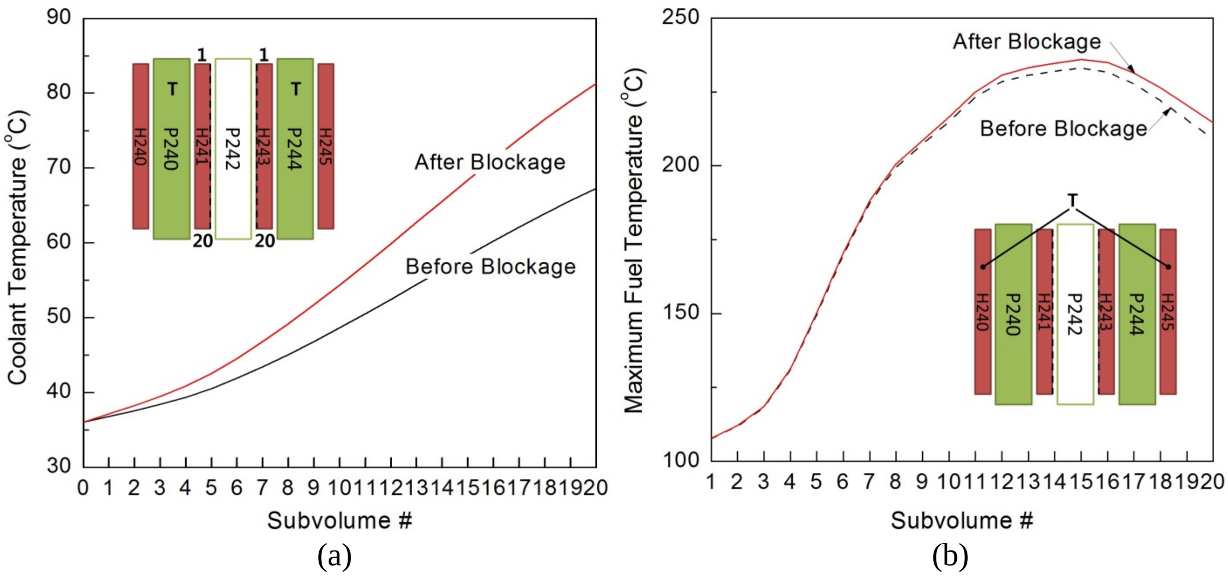


Figure 3. (a) Coolant temperature and (b) Maximum fuel temperature at the open channel fuels

3.2. Open Channel Fuels

Figure 3 shows the coolant temperatures and the maximum fuel temperatures of subvolumes at the open channel fuels. The coolant temperatures at the open channels increase by the increase of heat transferred from the closed channel fuels. However, the open channels still has enough cooling capability for the open channel fuels because the coolant still remains as a subcooled condition throughout the channel. By the increase of the coolant temperature, the open channel fuel temperature after the blockage increases higher than that before the blockage, but the difference is not significant to affect the fuel integrity. The temperatures shown in Figure 3(b) are the maximum temperatures of open channel fuels considering the engineering hot channel factors. Since the maximum fuel temperatures of the open channel fuels are far below the fuel blistering temperature of 400 ^{o}C, the fuel integrities are ensured.

4. Conductive and Radiative Heat Transfer

A one dimensional analysis including conduction and radiation was performed with simplified model and conservative assumptions. The previous analyses with RELAP5/MOD3.3 only consider the convective heat transfer by the coolant flowing through the channel, and do not consider a direct radiation and a conduction through the side plate. Since the temperature of closed channel fuel can increases up to the melting point, the consideration of radiation and conduction induces further increase of the fuel temperature at the open channel.

Figure 4 shows the heat transfer mechanisms of convection, conduction and radiation at the open channel fuel. The heat generated from the open channel fuel plates are transferred to the coolant by convection, but the heat generated at the closed channel fuel is conducted through the side plates and is radiated directly to the open channel fuels, increasing the temperature. Since the higher temperature of closed channel fuels result in more conservative consequences, the temperature is assumed as T_h =660^{o}C which is the highest melting point among the fuel and cladding materials.

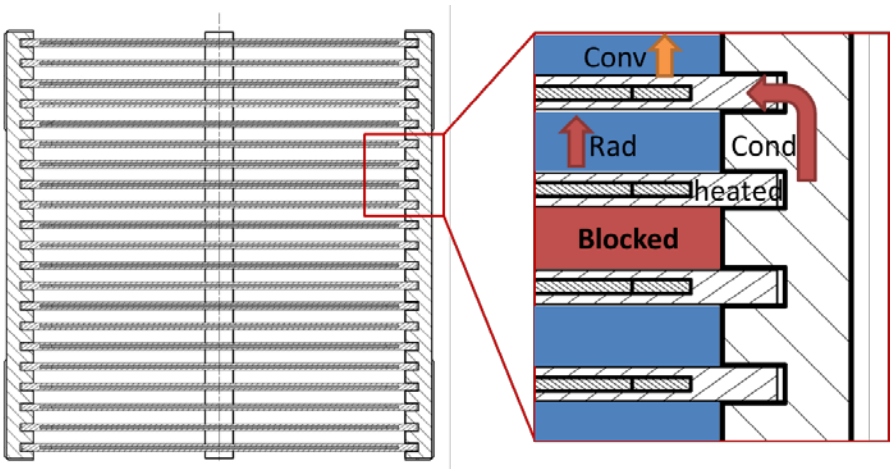


Figure 4. Heat transfer regimes from the closed channel fuel to the open channel fuel

Figure 5 shows the schematic of open channel fuel and the control volume of the fuel for the analysis. From the energy balance of the control volume, the following governing equation can be derived.

$$-kt\frac{d^2T(x)}{dx^2}=\dot{q}_G-2h[T(x)-T_C]+q_{Rad}$$

where the left hand side term is the conduction through the plate, and the second term at the right hand side is the convection to the coolant. The radiation term can be simplified with conservative assumptions of emissivity (ε), absorptivity (α), view factor (F) and the cold side temperature as

$$q_{Rad}=\sigma\varepsilon\alpha F\left[T_H^4-T^4(x)\right]\approx\sigma T_H^4\,.$$

And the effective heat transfer coefficient h is calculated considering the corrosion layer on the surface of the fuel plates as

$$h=\frac{h_s k_{ox}}{h_s t_{ox}+k_{ox}},$$

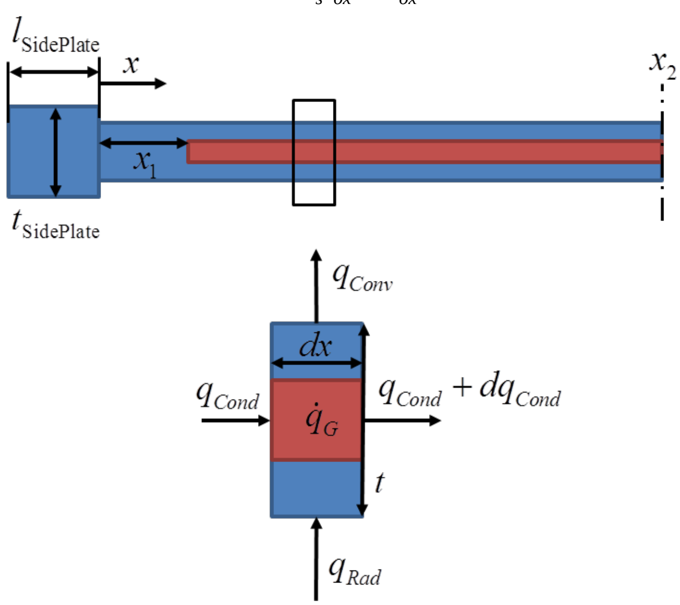


Figure 5. Schematic of fuel plate and control volume for one dimensional analysis

where h_s is the convective heat transfer coefficient at the fuel surface which is the minimum value from the RELAP5/MOD3.3 calculation for conservatism. The k_{ox} and t_{ox} are the thermal conductivity and the thickness of the corrosion layer, resepectively.

Then, the governing equation becomes simple nonhomogeneous ordinary equation, divided into two sections; the first section without fuel meat ($0<x<x_1$) and the second section with fuel meat ($x_1<x<x_2$), where x_2 denotes the center of the fuel plate.

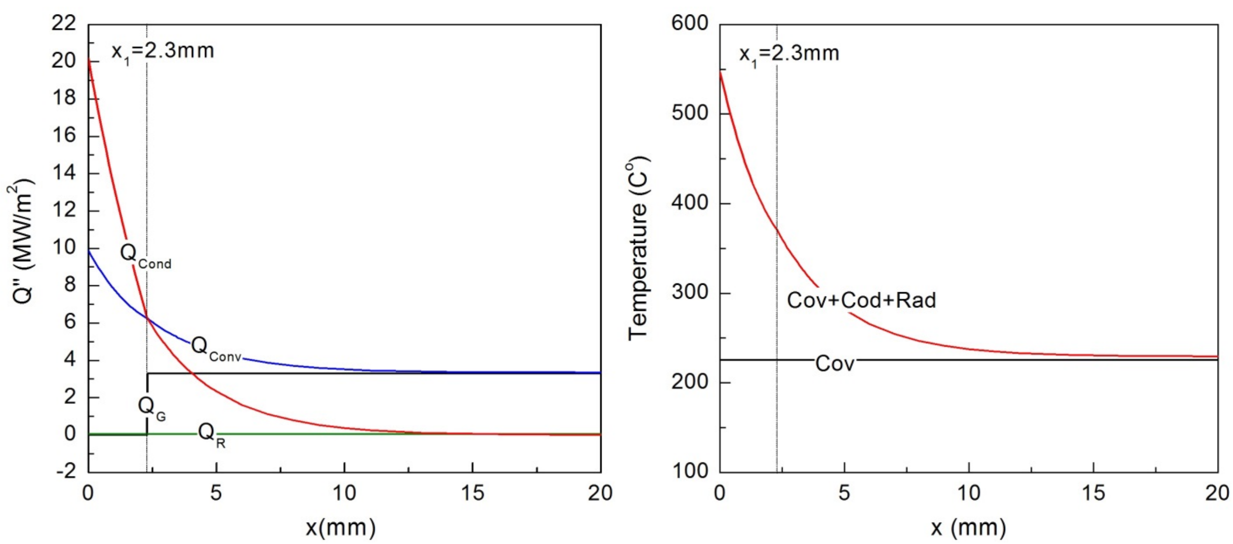
The boundary condition at x=0 is derived from the heat balance at the point as

$$\frac{t_{SidePlate}}{l_{sidePlate}}\left[T_H - T(x_0)\right] = -t\left.\frac{dT}{dx}\right|_{x_0} .$$

The boundary conditions at $x=x_1$ are continuous temperature and heat conduction along the fuel, and the boundary condition at $x=x_2$ is a reflective boundary condition from symmetry. From the governing equations and the boundary conditions, the temperature of the open channel fuel is estimated analytically .

Figure 6(a) shows the heat flux distributions at the open channel fuel with respect to the heat transfer regimes. At the end of fuel plate, conduction and convection are two dominant heat transfer mechanisms. However, the conduction decreases sharply after few mm and the convection and the heat generation become balanced.

Figure 6(b) shows the temperature distribution along the open channel fuel. The temperature at the fuel end (x=0) is 547 ^{o}C which is lower than the melting point of cladding material, and the fuel temperature where the meat starts ($x=x_1$) is 370 ^{o}C, which is far below the blistering temperature of fuel, 400 ^{o}C. The temperature approaches to that calculated with convection only, since the conduction diminishes along the fuel and the radiation is negligibly small. Therefore the integrity of open channel fuels are insured even considering the conduction and the convection from the closed channel fuels. Therefore, although the complete blockage of single fuel channel results in damage in the closed channel fuels, the damage do not propagate to the open channel fuels.



(a) (b)

Figure 6. (a) Heat fluxes of each heat transfer regime and (b) temperature distribution along the open channel fuel

5. Conclusion

A fuel damage propagation of 15-MW pool type research reactor is investigated during a complete blockage of a fuel channel. The fuel channels are modeled with conservative assumptions and the thermal hydraulic behavior of the channels and the fuels are analyzed with RELAP5/MOD3.3 which is modified to implement Kaminaga CHF correlation for rectangular channel. From the maximum fuel temperatures, the closed channel fuels are damaged by the accident, but the damages do not propagate to open channel fuels. In addition, direct heat conduction and radiation between the fuel plates are combined to the convection with one dimensional approximations and conservative assumptions. The temperature of open channel fuel increases at the edge where the heat flows into the plate, however, the temperature does not exceed the blistering temperature of fuel. Therefore, the damage of closed channel fuel does not propagate to the open channel fuels even considering the conduction and radiation.

Acknowledgement

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government (MEST) (NRF-2012M2C1A1026916).

6. References

[1] M. Kaminaga, K. Yamamoto, Y. Sudo, “Improvement of critical heat flux correlation for research reactors using plate-type fuel”, Journal of Nuclear Science and Technology 35, 943-951, 1998.

[2] Nuclear Safety Analysis Division, “RELAP5/MOD3.3 Code Manual Volume IV, Models and Correlations”, NUREG/CR-5535, Rev1, Information System Laboratories, Inc., 2002.