Impacts of Fuel Relocation on Fuel Behaviors during LOCA: Halden 650.4 Test

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1. Introduction

The fuel behavior following the Loss of Coolant Accident (LOCA) has received high attention from nuclear regulators as an effort to maintain the safety of the reactor during such accidents. The possibility of the axial relocation of fuel pellets that detached from the cladding was reported 35 years ago. However, its impacts were received a little attention until IFA-650.4 LOCA test performed by Halden reactor in 2006[1].

IFA-650.4 LOCA test had confirmed the fragmentation, relocation, and dispersal phenomena of high burn-up fuel during transient LOCA [2]. This paper aims at understanding the impact of fuel axial relocation on the fuel rod axial power, cladding temperature and cladding oxidation using FRAPTRAN2.0P1. Packing fraction with values of 0.5, 0.72, and 0.79 and fuel thermal conductivity with reduction percentage up to 80% were used for identifying the most important contributor on the overall fuel performance following LOCA.

2. Description of IFA-650.4 Test

The fourth Halden IFA-650 LOCA test have been conducted using a 480 mm fuel rod extracted from a high burnup PWR fuel rod (92.3MWd/kgU), which was irradiated for seven cycles with average power of 335, 275, 300, 190, 180, 170, and 160 W/cm respectively and discharged in June 1998[3].

IFA 650.4 test was conducted through five phases; the first phase was forced circulation and began with the steady-state operation for calibrating the rig power, where a linear heat generation rate (LHGR) of approximately 84 W/cm was reached. The reactor power then reduced to about 10 W/cm LHGR to achieve peak cladding temperature (PCT) of 800 °C.

Phase 2 of the test was natural circulation and was initiated by the disconnection of the rig from the outer loop. The water was allowed to flow-up between the fuel rod and flow separator and flow-down between flow separator and flask wall.

Phase 3 was the blowdown during which the channel pressure decreased to 3-4 bars by the opening of dumping tank valves. Following the blowdown, phase 4 began with the inadequate cooling that led to a rapid increase in fuel cladding temperature. The ballooning and burst were detected at 617 s following the blowdown. In phase 5, the test was ended by reactor scram, where the cladding was cooled down to 400 °C[4].

3. Modeling

3.1 Fuel rod conditions

The axial relocation of fuel rod following LOCA is considered a great reactor safety issues since it increases local heat load and fastens the failure. Fuel behavior of Halden IFA 650.4 LOCA test was calculated using the analytical tool FRAPTRAN2.0P1.

Based on the Quantum Technology fuel relocation model, the thermo-mechanical behavior of fuel rod was analyzed[1]. The calculations were done by discretizing the fuel rod into 20 and 22 equal-length axial and radial segments respectively and the cladding was divided into 5 equal-length segments. The experiment specifications are shown in Table 1.

Table1: Halden IFA-650.4 LOCA test's information[5].

Specification	Details
Rodlet active length	480 mm
Cold free volume	21.5 cm^3
Fill gas composition (vol%)	95 Ar + 5 He
Fill gas pressure at 295 K	4.0 MPa
Cladding tube material	Duplex
Cladding tube base material	Zircaloy-4
Outer surface liner material	Zr-2.6 wt%Nb
Heat treatment	SRA
Outer surface liner thickness (nominal)	100 μm
As-fabricated cladding outer diameter	10.75 mm
As-fabricated cladding wall thickness	0.725 mm
Pre-test oxide thickness (mean)	10 μm
Pre-test oxide thickness (max)	11 μm
Pre-test hydrogen concentration	50 wppm
Pre-test fast neutron fluence (> 1Mev)	1.52×10^{26} m^{-2}

3.2 Boundary conditions

The Peak Linear Heat Generation Rate (LHGR) was set to be 20.7 kW/m. The internal gas pressure was adjusted to simulate the time of fuel rod burst of the experiment, and the burst strain was fixed as 0.62. Modeling technique of cladding temperature as a boundary condition was developed to see the behavior of fuel inside of fuel cladding only. Therefore, the heater temperatures were used as the coolant temperatures to observe the cladding temperature change with fuel relocation, while the heat transfer coefficients were imposed to simulate the experimental results of cladding temperatures.

4. Results and Discussions

4.1. Cladding outside surface temperature

The timely variation of cladding outside surface temperature is shown in Figure 2. The measured temperature was given using TCC1 at position 400 mm, while the calculated temperature was determined at position 480 mm above the bottom (node 20). There is a good consensus between the calculated and measured temperature values, where the temperature value increases until it reaches the peak of value ~1040 K at rupture time ~315.5 sec due to the insufficient cooling. FRAPTRAN results predicted that the cladding rupture would occur 10 seconds earlier when the fuel relocated in comparison to the case without relocation. This suggests that the axial relocation of fuel into the ballooning region occurred at a time equivalent to the difference in the rupture time between the two mentioned cases.

Following the rupture time, FRAPTRAN shows a rapid reduction in the cladding temperature when the fuel is rapidly relocated in comparison to the case of no relocation, due to the increase in the cooling surface area in the balloon region.

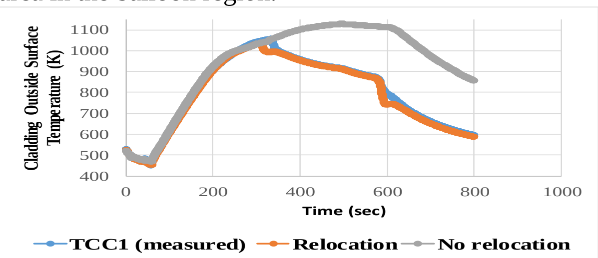


Figure 2: Cladding outside surface temperature variation with time.

Cladding outside surface temperature along the fuel rod at the rupture time is shown in Figure 3. The relocation of fuel led to a distinguished temperature peak with a value of ~1080 K within the ballooning region. On the other hand, FRAPTRAN results show that if no fuel relocation occurs then the cladding temperature will maintain its uniformity along the fuel rod during the rupture time.

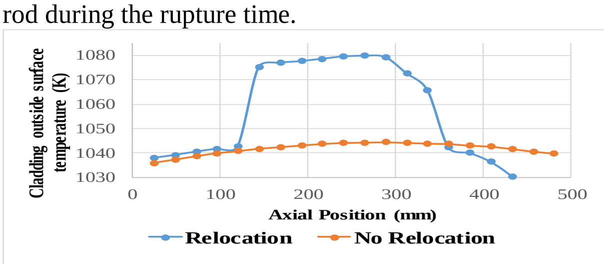


Figure 3: Cladding outside surface temperature versus fuel axial position during rapture at 315.5 sec.

To understand the long-term effect of fuel axial relocation after the rod failure, the cladding outside surface temperature was calculated at 800 sec as shown in Figure 4. The cladding temperature had decreased by 30 K at the end of time in case of fuel relocation. These results show that the effect of axial relocation is a critical issue at the time of rupture and its impact on fuel performance becomes comparable to the case without relocation late after the rupture.

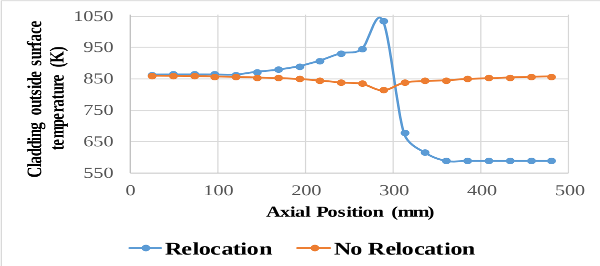


Figure 4: Calculated cladding outside surface tempreture versus axial position at 800sec.

4.2. Equivalent cladding reacted (ECR)

The axial relocation of fuel can stimulate the cladding oxidation due to the long-term cladding heating. The fraction of cladding thickness that is oxidized is known as Equivalent Cladding Reacted (ECR). The ECR versus the axial positions was analyzed at the time of 800s.

As shown in Figure 5, the axial relocation of fuel led to a significant increase in the ECR of about 6 times larger than the value of ECR when no fuel relocation occurred.

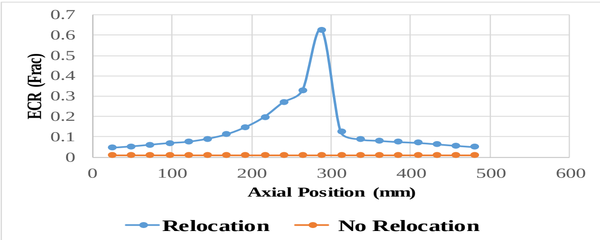


Figure 5: Equivalent cladding reacted (ECR) versus axial position at the rupture time of 315.5 sec.

4.3. Cladding hoop strain

The cladding hoop strain along the fuel rod is shown in Figure 6. Its value increases gradually within time: the calculated value of hoop strain was 10% at 10 seconds before the rupture, while it became 20 % at 3 seconds before the rupture. However, at the time of rupture, the hoop strain reaches 62%.

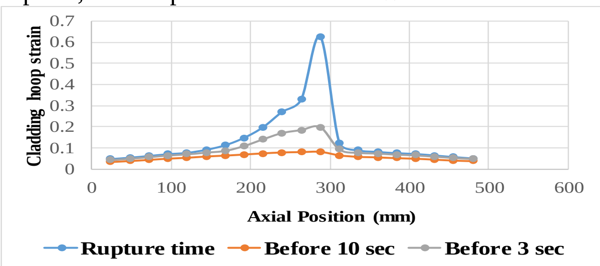


Figure 6: Cladding hoop strain values along the fuel rod up to the time of cladding rupture (315.5 sec).

4.4. Axial Power

At the rupture time, the axial power along the fuel rod was analyzed in Figure 7. FRAPTRAN results show that the axial power suddenly increased at the ballooning region with a value of 5.3 kW/m, and then the value became zero at a position of the height of 312 mm above the bottom indicating the relocation of fuel into the balloon region. On the other hand, uniform axial power was observed in the case of no relocation.

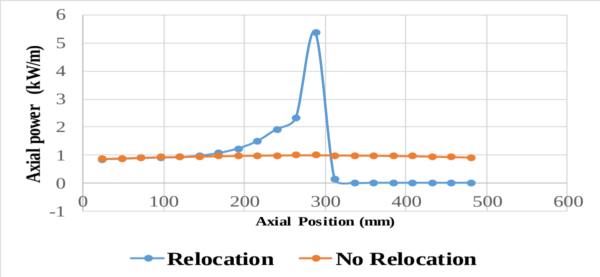


Figure 7: Axial power versus axial position at rapture time of 315.5 sec.

4.5. Gap heat transfer coefficient

As previously mentioned, the peak values of cladding temperature and axial power were observed in the ballooning region in which crumbled fuel were accumulated and led to the closure of the pellet-cladding gap. As shown in Figure 8, if the fuel axially relocated to the balloon region, then the gap heat transfer coefficient (HTC) is significantly increased in comparison to the case of no fuel relocation.

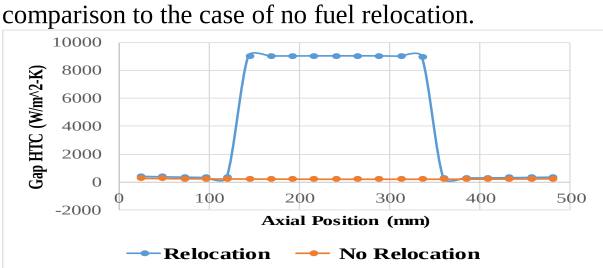


Figure 8: Gap heat transfer coefficient (HTC) along the fuel rod during the rupture time of 315.5 sec.

4.6. Sensitivity Study: relocation case

4.6.1. Cladding temperature

The impact of packing fraction (P.F) and thermal conductivity on the time at which fuel failure may occur was analyzed in Figure 9. The packing fraction inversely affects the rupture time: the rupture occurred at 327 seconds when the P.F=0.5, while it occurred at 305 seconds when P.F=0.79. On the other hand, the reduction in fuel thermal conductivity delays the rupture occurrence: For 80% reduction in the thermal conductivity, the rupture occurred at 313 seconds, while it occurred at 309 seconds when the reduction is 20%.

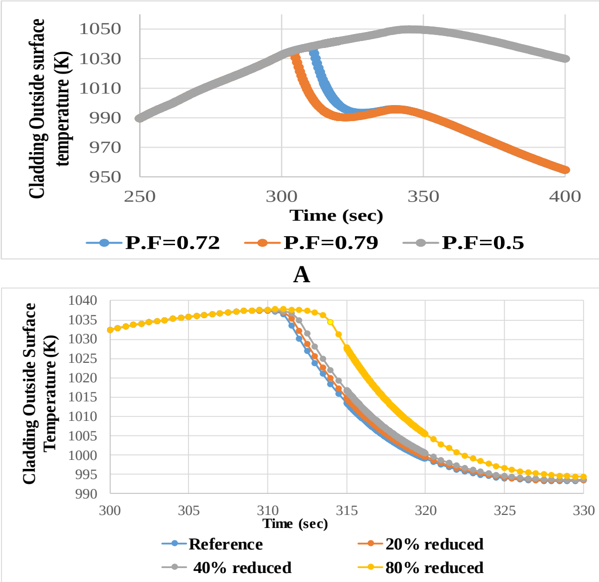


Figure 9: The influence of packing fraction (**A**) and crumble thermal conductivity (**B**) on cladding temperature with time.

Figure 10 shows the impact of the packing fraction and thermal conductivity on the cladding outside surface temperature along the fuel rod. The high packing fraction is connected the highest temperature value at the ballooning region. As shown in Figure 10-A, the temperature was 1100 K for P.F of 0.79 at 288 mm above the bottom, while it was 1080 K when P.F was 0.72, on the other hand, the temperature was uniformly distributed along the rod when P.F was 0.5 and no ballooning region was identified. Figure 10-B shows that the cladding temperature reduced gradually as the thermal conductivity reduced.

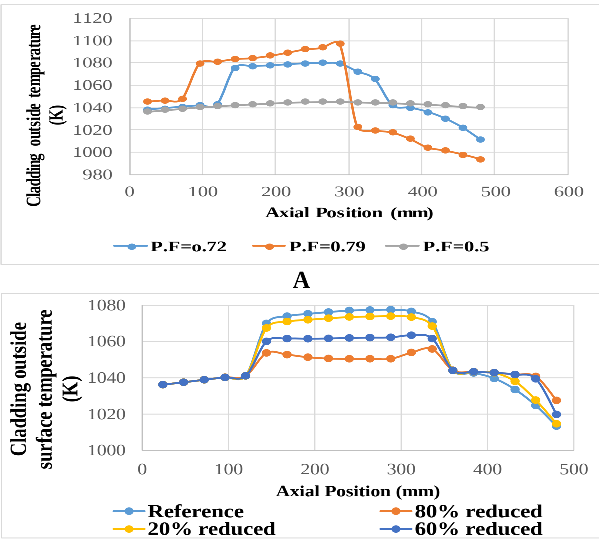
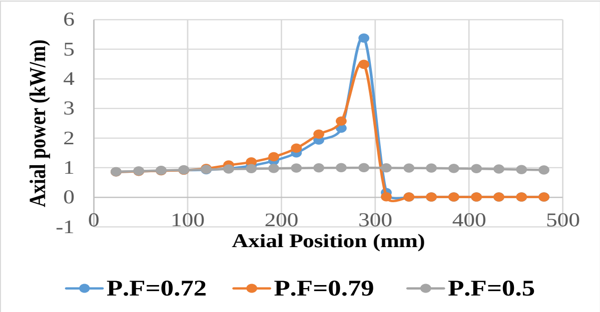


Figure 10: Cladding outside temperature along the fuel rod at rupture time of 315.5 sec: **A.** Packing fraction impact, **B.** Thermal conductivity impact.

4.6.2. Axial Power

Figure 11-A shows the impact of packing fraction on the axial power: the higher packing fraction led to higher axial power peak at the ballooning region and wide zero-power region following the balloon region: for P.F of 0.79, the zero-power region began at 312 mm, while no zero-power region when P.F was 0.5. In addition, Figure 11-B shows that the axial power value in the balloon region reduced with the reduction of thermal conductivity and as the thermal conductivity reduced the zero-power region area reduced. Figure 11 shows that the impact of thermal conductivity on the zero-power region area is clearer in compare to the packing fraction impact.



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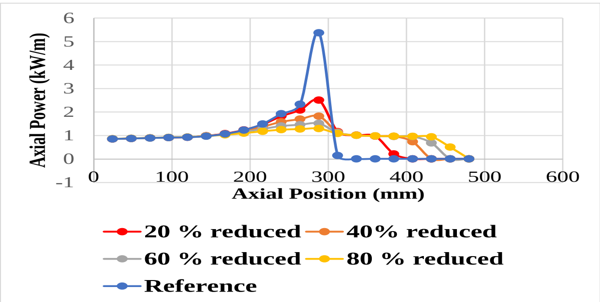

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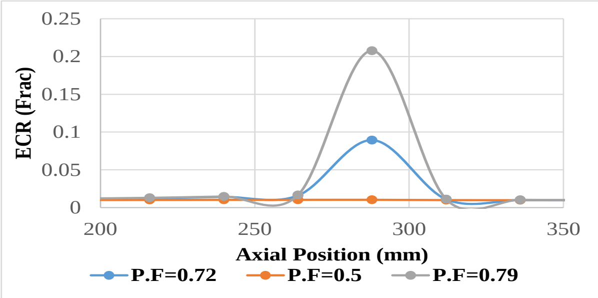
Figure 11: Variation of axial power along the fuel rod at rupture time of 315.5 sec. **A.** Packing fraction impact, **B.** Thermal conductivity impact.

4.6.3. Equivalent cladding reacted (ECR)

The effect of packing fraction (P.F) and fuel thermal conductivity on the equivalent cladding reacted (ECR) are shown in Figure 12. In Figure 12-A, increasing the value of packing fraction lead to increase ERC peak value: when P.F=0.79, the ERC equals 0.2. However, when the packing fraction value decreased to 0.5, the ERC uniformly distributed along the rod and no ballooning region was identified. Figure 12-B shows that the fuel thermal conductivity has a direct impact on ERC and when the thermal conductivity of fuel reduced, the ECR reduced.



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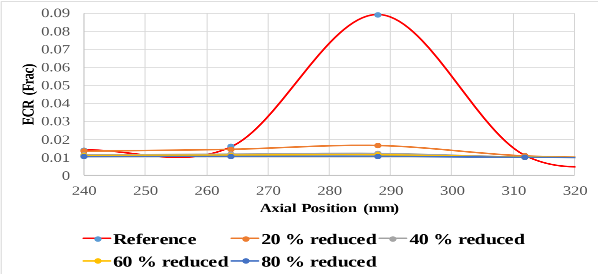

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Figure 12: ECR value along the fuel rod at rupture 315.5 sec. A: Packing fraction Impact, B: Thermal conductivity impact.

4. Summary

The impacts of the axial fuel relocation on fuel behaviors during LOCA were investigated by using the results of Halden IFA 650.4 LOCA experiment. Followings can be summarized.

- Axial fuel relocation of the Halden IFA 650.4 test leads to a significant increase in local power, temperature and oxidation of the cladding in the ballooning region.
- Packing fraction and fuel thermal conductivity of crumbled fuel also showed strong impacts on axial power profile, cladding temperature and oxidation during LOCA transient.

7. REFERENCES

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