Fuel Fragmentation, Relocation, and Pulverization Models and Criteria for Fuel Behavior Evaluation of Halden IFA 650.4 LOCA Test using FRAPTRAN

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1. Introduction

Understanding the fuel behavior during Loss of Coolant Accidents (LOCAs) in Light Water Reactors (LWR) is of importance to maintain the safety of nuclear reactors. It was confirmed in several tests, including the Halden IFA-650 tests that have been conducted in Halden, Norway in 2006, such that UO_2 fuel with an average burnup that exceeds 60 MWd/kgU may pulverize into fine fragments during LOCA [1]. In addition, it is also concluded from the conducted tests that if cladding ballooning followed by successive burst occurs during LOCA, there is a high possibility for the fragmented and pulverized fuel to relocate downwards along the fuel rod, which is referred to as axial fuel relocation [1, 2]. In that sense, axial fuel relocation is of safety concern due to the resulting change in the heat distribution along the fuel rod as well as the potential increase in the amount of fuel material released into the coolant after cladding failure and burst.

Currently, the mechanism of fuel pulverization is not completely understood. Therefore, several hypotheses have been proposed that help understand this phenomenon. The most predominant one is that fuel pulverization occurs by cracks that are initiated because of the overpressurized pores and bubbles filled with fission gases [1-3]. In that sense, several criteria have been applied and models have been developed to predict fuel fragmentation based on the size, shape, number density, and internal pressure of the fission gas bubbles.

In this study, the fuel behavior is evaluated using a modified FRAPTRAN transient fuel performance code [1, 4]. The fuel fragmentation and relocation criteria include the relocation model already applied in FRAPTRAN 2.0P1, in addition to two criteria that have been studied and reviewed by Jernkvist et al. [2]. The adopted LOCA test in the modelling and simulation is the Halden 650.4 test.

2. Halden IFA-650.4 LOCA Test Description

Halden IFA-650.4 has been done on a 480 mm fuel rodlet with an average fuel burnup of 92.3 MWd/kgU that had been sampled from a pressurized water reactor (PWR) fuel rod. The rod has had been in a commercial power reactor for seven operating cycles. The average power of the rod was 335, 275, 300, 190, 180, 170, and 160 W/cm for the seven cycles, respectively [5]. Table 1 shows the design parameters and the pre-test conditions of the test.

IFA 650.4 test consists of five phases. The first phase began with the steady-state operation to calibrate the rig power. The linear heat generation rate (LHGR) of approximately 84 W/cm was achieved. The reactor LHGR was then reduced to about 10 W/cm to reach a peak cladding temperature (PCT) of 800 °C. The second phase 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. The third phase was the blowdown scenario as the channel pressure decreased by opening the dumping tank valves. Following the blowdown, the fourth phase 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. The fifth phase includes the end of the test by reactor scram, where the cladding was cooled down to 400 °C [6].

Table 1: Halden 650.4 Test Design and Pre-test Parameters [1]

Parameter	**650.4**
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. The Currently Available Model and Criteria

The first model that has been already implemented in FRAPTRAN 2.0P1 has been developed by Jernkvist et al. [3]. Based on the aforementioned 2014 review of data, an empirical threshold for gas-induced fuel fragmentation under LWR LOCA conditions was proposed. The threshold was formulated in terms of local fuel temperature versus local burnup in a first attempt to define combinations of these two parameters, for which gas-induced fragmentation is practically negligible [2].

This model states that fuel pulverization may occur only in those parts of the fuel pellets that have a local burnup above 70 MWd/kgU. In addition, Pulverization occurs in the high burnup material only if the local temperature exceeds a critical threshold and the pellet-cladding contact pressure is lower than 50 MPa. The applied temperature threshold is shown in Fig. 1.

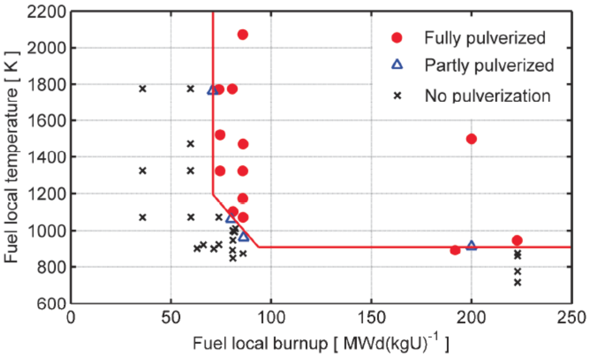

Fig. 1. Temperature threshold for pulverization in comparison with experimental data [3]

In addition to the model implemented and FRAPTRAN 2.0P1, several criteria have been considered to accurately model fuel fragmentation based on the formulation of an appropriate analytical criterion, by which fragmentation of the material can be predicted based on the size, shape, number density, and internal pressure of fission gas-filled bubbles. Two main criteria that showed adequate suitability or use in computer programs intended for analyses of the thermal–mechanical behavior of light water reactor fuel rods in accident conditions, including LOCA.

One of the criteria is by Olander (1997) and it is based on grain boundary stress. On the other hand, the other criterion is by Chakraborty, Tonks, and Pastore (2014) and it is based on linear elastic fracture mechanics [2]. The criteria provide an estimate for the gas pressure required in intergranular bubbles for the grain boundary to break. The details of these models are thoroughly discussed in Ref. [2]. The comparative assessment of the criteria is to be conducted based on the influence of fission gas bubble radius, fractional coverage of grain size, and the pre-accident hydrostatic pressure.

4. Preliminary Results

The initial stage of the analysis is to show the effect of the fuel fragmentation and relocation on the fuel behavior of Halden 650.4 test using the currently implemented model by Jernkvist et al. [3] in FRAPTRAN. Therefore, FRAPCON-3.5 has been used to generate the necessary burnup dependent fuel rod initial conditions before LOCA. Fig. 2 shows the rod average burnup as a result of FRAPCON simulation for the 650.4 test. Fig. 2 shows that the burnup matches the experimental results that have been reported [1, 5, 6].

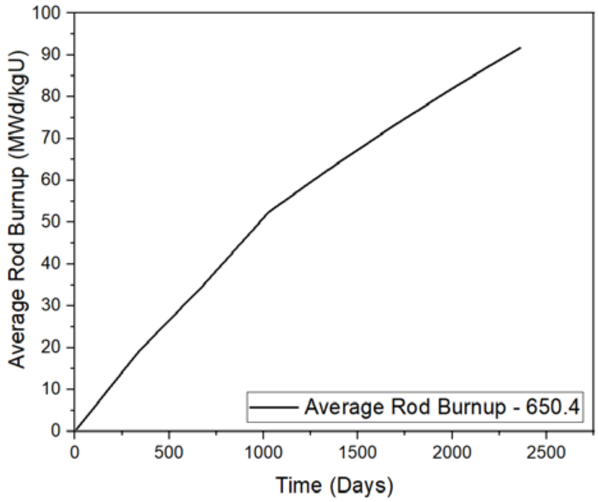

Fig. 2. Average fuel rod burnup obtained from FRAPCON-3.5

After obtaining the burnup dependent fuel rod initial conditions from FRAPCON-3.5, the effect of fuel fragmentation and relocation has been simulated using FRAPTRAN 2.0P1 that has the model developed by Jernkvist et al. [3] implemented. Fig. 3 shows a comparison between the cladding outside temperature for the 650.4 LOCA test with and without axial relocation. It is important to mention that cladding burst and fuel fragmentation and relocation has occurred at the axial node number 12 as the fuel rod has been divided into 24 axial nodes. Fig. 3 shows a clear difference and reduction in the cladding outside temperature when the fuel axial relocation model is applied.

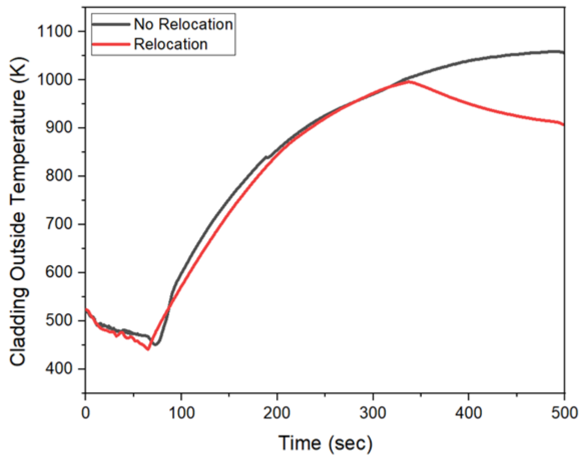

Fig. 3. A comparison of the cladding outside temperature during the 650.4 LOCA test at node 12 with and without the axial relocation model.

In addition, the equivalent cladding reacted (ECR %) 0.5 s after cladding failure has been compared when the axial relocation model is activated. The comparison is shown in Fig. 4. A clear difference and a spike in the ECR percentage value are noted when the axial relocation model is activated. However, the thermal-hydraulics boundary conditions need to be modified and specified more accurately to match the experimental results reported in Ref. [1]. This leads to more accurate quantification of the ECR value during LOCA when the fuel axial relocation model is applied.

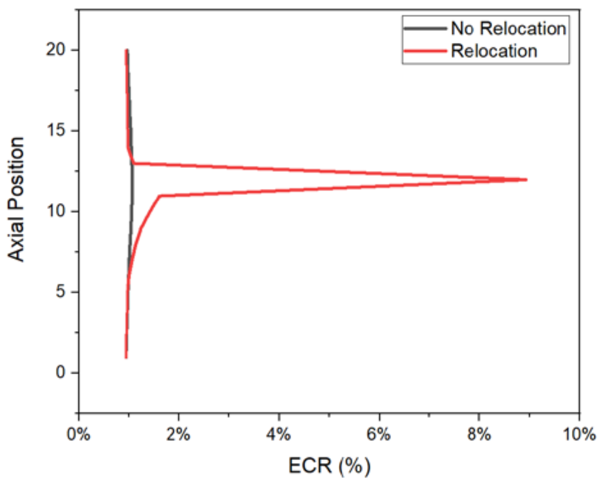

Fig. 4. A comparison of the equivalent cladding reacted (ECR %) during the 650.4 LOCA test 0.5 s after cladding failure with and without the axial relocation model.

In the current model that is applied to FRAPTRAN 2.0P1, the mass fraction of fine fuel fragments is calculated by the use of an empirical threshold for pulverization of high burnup fuel during temperature excursions. The results show that this empirical model significantly overestimated the degree of fuel pulverization. Therefore, the threshold should be replaced with a refined, mechanistically based, model for fuel pulverization, which accounts for more parameters than just the fuel local burnup and temperature. In addition, the impact of mechanical constraint from the cladding and effects of pre-LOCA operating history for the fuel should be considered.

In that sense, the two criteria discussed previously are being implemented in the modified FRAPTRAN to establish a comparison of these models criteria with the currently existing model in FRAPTRAN 2.0P1 by Jernkvist et al. [3]. This serves as a starting point of developing a new model that links fuel fragmentation and pulverization to the local fuel porosity and distribution of gaseous fission products in the fuel.

5. Conclusions

The fuel behavior under LOCA shows a significant difference when the fuel axial relocation model that is currently applied in FRAPTRAN 2.0P1 is activated. The difference is evaluated by comparing the cladding outside temperature and the equivalent cladding reacted (ECR %) with and without the axial relocation model. However, the thermal-hydraulics conditions that have been used in FRAPTRAN simulation need to be modified and enhanced to accurately quantify the effect of fuel axial relocation on the fuel behavior under LOCA.

In addition, the current model that is applied in FRAPTRAN 2.0P1 is a function of an empirical threshold for pulverization of high burnup fuel during temperature excursions. This threshold-based model significantly overestimated the degree of fuel pulverization. Therefore, a more refined, mechanistic model for fuel pulverization, which accounts for more microstructural parameters than just the fuel local burnup and temperature is needed to be developed.

As a starting point for the development of an advanced model, a comparison between two criteria with the currently existing model in FRAPTRAN 2.0P1 is being constructed. Comparing the most suitable models aims to develop a new model that links fuel fragmentation and pulverization to the local fuel porosity and distribution of gaseous fission products in the fuel.

ACKNOWLEDGMENTS

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