Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 20-21, 2022

Capability of DRACCAR Code for Fuel Fragmentation, Relocation, and Dispersal (FFRD)

Chiwoong CHOI [a*], Seung Wook Lee [a], and Kwiseok Ha [a]
[a]*Reactor System Safety Research Division, Korea Atomic Energy Research Institute (KAERI), Daedeok-Daero, 989-111, Yuseong-Gu, Daejeon, South Korea*
[*]*Corresponding author: cwchoi@kaeri.re.kr*

1. Introduction

In order to response the revision of the ECCS regulation, new models of fuel fragmentation, relocation, and dispersal (FFRD) were recently implemented in SPACE code. There is a few code having a capability for prediction of FFRD. FRAPTRAN has the FFR model based on QT model[1]. BISON has the same model to the QT model [2]. DRACCAR code has own FFRD models, which are developed by IRSN[3]. In this study, the FFRD model in the DRACCAR code is reviewed. And, using Halden IFA-650 tests, the DRCCAR code is validated. In addition, sensitivity tests for major input parameters are carried out to understand capability of DRACCAR code.

2. DRACCAR code and its FFRD model

The DRACCAR code is developed by IRSN to simulate fuel assembly mechanical behavior and coolability assessment during a LOCA transient. The DRACCAR is a platform that couples its thermo-mechanical code, ICARE3D, to different thermal-hydraulic codes, CATHARE or CESAR. Therefore, DRACCAR is a multi-physic code involving mechanics, heat transfer, chemistry and hydraulics. DRACCAR has validated with various separate and integral effect tests including PERICLES, ROSCO, FEBA, SEFLEX, and ACHILLES, PHEBUS, CORA, REBEKA, SFP, etc. And DRACCAR development is influenced by other on-going OECD/NEA projects dedicated to LOCA, such as Halden or SCIP.

DRACCAR has a FFRD model, named 'RELO' structure [4]. The fuel relocation occurs in the cladding balloon when the cladding bursts or its strain is sufficient. They considered two kinds of phases: radial expansion and relocation of fuel fragment as shown Fig. 1.

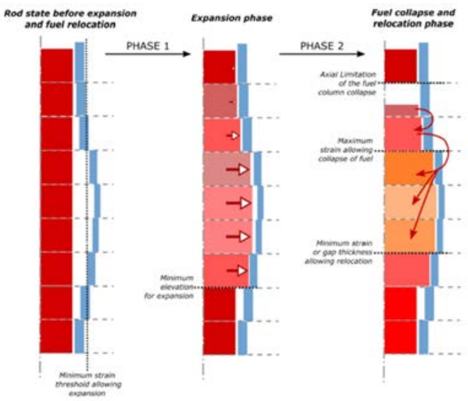

Fig. 1 Expansion and relocation of fuel fragment in DRACCAR

The FFRD model in DRACCAR has various optional sub-models, which are provided to input parameters shown in Table 1. For example, the 'CRIT' parameter of 'BURST' means that the fuel relocation is initiated when the clad burst occurred. And fuel dispersal is explicitly defined by user with 'LOST' parameter, which means that DRACCAR has no physical dispersal model yet.

Table 1 Input parameters related to the FFRD model

parameters	description
FILLRT[1]	balloon filling ratio
CRIT	Criterion for fuel relocation: BURST or STRAIN
GAPMIN	Minimum gap thickness allowing axial fuel relocation
RESGAP	Residual gap thickness maintained between fuel and cladding
ZMAX	Maximum elevation of fuel pellets columns concerned by relocation
LOST	Fraction of fuel dispersal

[1]the fuel filled volume ratio (1-porosity)

3. Validation with Halden Tests

3.1 Halden IFA-650 Test

In order to evaluate prediction capability of FFRD model in DRACCAR code, Halden IFA-650 tests, which are simulated to LOCA, are selected. Fig.2 shows a test rig in Halden IFA-650 test. The modified single fuel rod is instrumented and placed in the center of the rig. The rod is surrounded by an electrically heated shroud and a pressure flask. The heated shroud is part of a flow separator, which separates the coolant into a central channel adjacent to the fuel rod and an outer annulus. The heated shroud provides boundary conditions that resemble the heating effects of nearby fuel rods with similar power. Thus, the temperature of the test rod is controlled both by nuclear and electrical heating. The pressure flask is connected to a water loop. There are bottom inlet and top outlet tubes. The LOCA simulation was initiated by opening valve to a blowdown tank. After the blowdown, the heat-up period of the LOCA was simulated by turning on the additional electrical heater. And no actions are taken until the test terminated by switching off the electrical heater and scramming the reactor. The IFA-650 test rig instruments measured fuel rod elongation, fuel mass distribution, gas pressure, coolant temperature, clad temperature at different axial locations.

Table 2 Halden IFA-650 test conditions

	1,2	3	4	5	6	7	8	9	10	11	12	13	14
Target PCT [℃]	Fresh fuel	800	800	1100	850	1100	System check-out test with fresh fuel	1100	850	1000	850	870	850
Fuel Type		PWR	PWR	PWR	VVER	BWR		PWR	PWR	VVER	BWR	BWR	BWR
Rod ident.		V1-51 5/3	14D/7	V1-51 5/7	J13	AEB-0 70E4		14D/3	F08/3	J13/3	AEB0 72-E4	AEB0 72-4C	AEB0 72-J9
Span no.		2-3	5-6	5-6	-	3		2-3	3	-	3	-	-
Fuel length [cm]		48	48	48	48	47		48	44	48	38	38	36
Cycles		6	7	6	4	3		7	6	4	5	7	7
Burnup [MWd/kgU]		81.9	92.3	83.4	55.5	44.3		89.9	61.0	56.0	72.3	74.1	70.8
Oxide thick [μm]		18-27	10	65	5	10		7-8	20-30	5	40	20	-
Hydrogen [ppm]		250	50	650	100	44		30	150-220	100	300	300	-
Cladding		Zry4/ 1.47% Sn	Zry4/ 1.47% Sn	Zry4/ 1.47% Sn	E110	LK3/L		Zry4/ 1.47% Sn	Zry4	E110	LK3/L	LK3/L	LK3/L
Do/thick [mm]		10.75 /0.72 5	10.75 /0.72 5	10.75 /0.72 5	9.13/ 0.68	9.62/ 0.63		10.75 /0.72 5	9.5/0. 57	9.13/ 0.68	9.62/ 0.63	9.62/ 0.63	9.62/ 0.63
Liner [μm]		150	100	150	No	Yes		100	No	No	Yes	Yes	Yes
Heat Treatment		SRA	SRA	SRA	Stand	Stand		SRA	SRA	Stand	Stand	Stand	Stand
Pressure [bar]		40	40	40	30	6		40	40	30	20	20	20

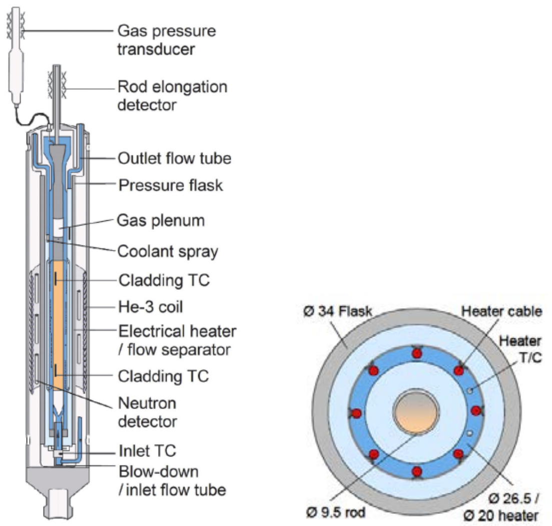

Fig. 2 Schematic of the IFA-650 test section: axial (left) and radial (right)

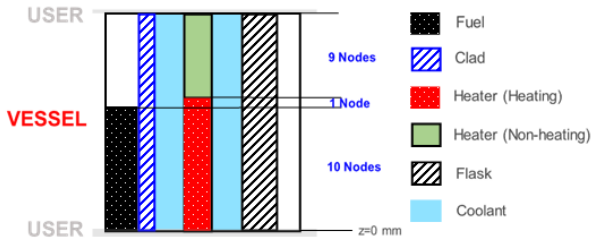

Fig. 3 Axial modeling of Halen IFA 650 test rig for DRACCAR

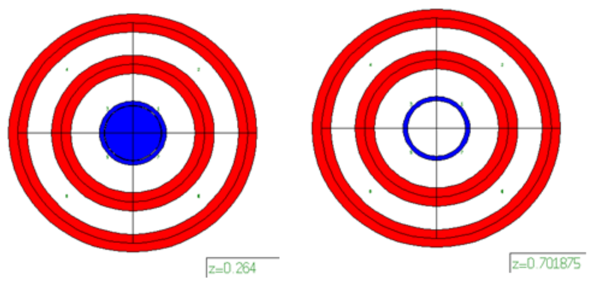

Fig. 4 Radial modeling of Halden IFA-650 test rig for DRACCAR: with fuel(left) and with gas plenum(right)

Halden IFA-650 tests conducted 14 cases with various fuel type, burnup, temperature, etc as shown in Table 2. In this study, test no. 2, 4 and 9 among PWR fuel types are selected to validate FFRD model in DRACCAR code. The higher burnup cases are selected, since FFRD phenomena is critical for the high burnup (>70MWd/kgU) [5]. Moreover, the test no.2 of a fresh fuel case is added as reference.

3.2 IFA-650 Modeling for DRACCAR

ICARE and CESAR coupled modules in DRACCAR are applied for calculation of Halden IFA-650 tests. Fig.3 shows the modeling of Halden IFA-650 test rig for DRACCAR. The fuel, clad, heater and flask are modeled with same axial elevation. So, the empty region above the fuel is added. Fig. 4 shows cross-sectional modeling at fuel and gas plenum regions, respectively. The break is simulated at the bottom inlet region. And the measured coolant pressure are applied as the break boundary condition during transient. In addition, to match initial temperature rise behavior, the clad emissivity is adjusted, because the clad temperature is one of most important parameter clad deformation and rupture. DRACCAR provides several optional models for deform and burst in a clad. In this study, based on the sensitivity test, the STRAIN model with Edgar material data base(MDB) is applied [6]. The fuel filling ratios are set to the calculated values from the QT model.

3.3 IFA-650 No.2 Results

Generally, when a clad temperature is increased during a LOCA transient, cladding ballooning and burst are expected. Thus, the gap between fuel and clad in the ballooned region is increased. If the particle size of fuel is small enough to move downward, the fuel mass can be relocated. Thus, the temperatures in the fuel reduced and

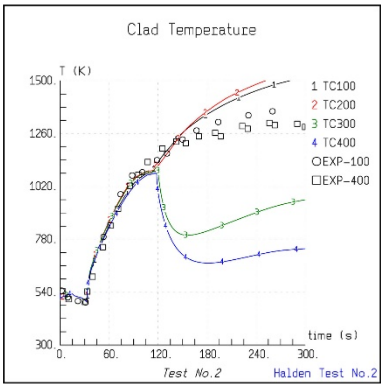

Fig. 5 The clad temperatures for IFA-650 Test No.2 (default: GAPMIN=0.2mm)

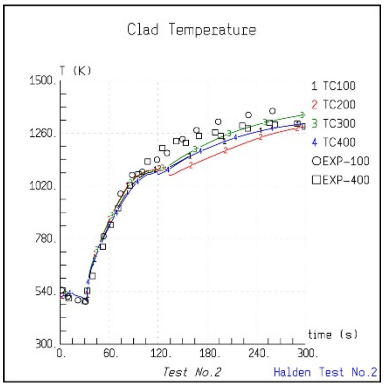

Fig. 6 The clad temperatures for IFA-650 Test No.2 (GAPMIN=5.0mm)

added regions are decreased and increased, respectively. Test No.2 is the test with fresh fuel. Thus, the fuel is not relocated and the clad temperature is not changed during a heat-up region. Fig. 5 shows the comparison of the clad temperature (TCCs). The clad temperature drops at 300mm and 400mm locations. It means the DRACCAR predicts a fuel relocation even though the fuel is fresh condition. In other words, DRACCAR has no limitation for fuel relocation for large fuel fragments. It means that DRACCAR Code has no model for fuel fragmentation and its relation to fuel relocation. In this calculation, GAPMIN = 0.2mm is applied, as recommended by QT model [1]. However, the GAPMIN indicates threshold value for fuel relocation. In addition, it must be highly depends on the fuel particle size. For example, when fuel particle size is large, the GAPMIN must be large enough. When the GAPMIN of 5mm is applied, Fig. 6 shows clad temperature drop is disappeared due to suppression of the fuel relocation.

3.4 IFA-650 No.4 Results

The test no.4 has the highest burnup of 92.3 MWd/kgU. So, the fuel fragment size must be very small by pulverization process [5]. This means fuel relocation can occur easily. The fuel deformation is well predicted by DRACCAR. Fig. 7 show axial fuel relocation predicted by DRACCAR. The rupture is slightly delayed comparing to the experiment. However, fuel relocation is

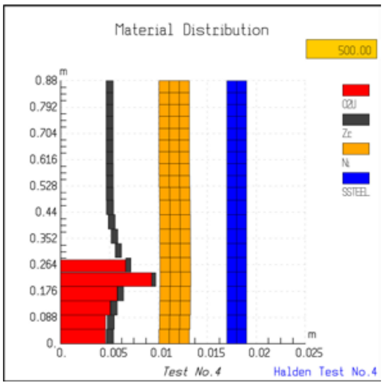

Fig. 7 Axial clad deformation and fuel relocation for IFA-650 Test No.4

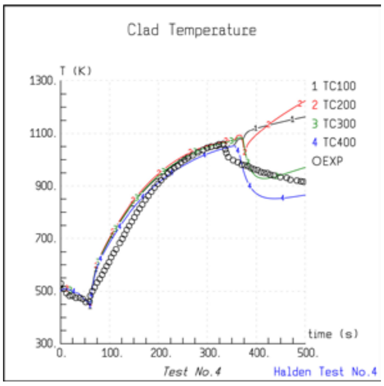

Fig. 8 The clad temperatures for IFA-650 Test No.4

well predicted, thus clad temperature (TC-400) is decreased as similar to the experiment (Fig. 8).

3.4 IFA-650 No.9 Results

The test no.9 has burnup of 89.9 MWd/kgU. It has also very high possibility for fuel relocation. The predicted clad deformation is very different from experiment as shown in Fig. 9. According to the fuel power distribution, generally the rupture location is near center. In this test, the rupture occurs at very bottom location. However, the rupture timing is well predicted. Fig.10 shows the clad temperatures for different elevations. TC300 and TC415 are decreased and TC100 and TC200 are increased. However, the temperature drop is much higher and temperature rise is less than the experiment. The possible reason of the under-estimation of the temperatures at the lower region can be the predicted rupture location. In other words, the relocated fuel mass at the TC100 is much lesser than the experiment. Moreover, in the experiment, fuel in the top region is not relocated. It can be a reason for the under-estimation of TC415. DRACCAR has optional input of ZMAX, which gives limitation of fuel relocation region. When the ZMAX of 400mm is applied, the fuel located over the ZMAX is neglected for the fuel relocation. Fig. 11 shows that TC415 is increased due to remained fuel comparing to the result in Fig. 10. DRACCAR has various optional models for various features. However, these options should be provided as input parameters by user.

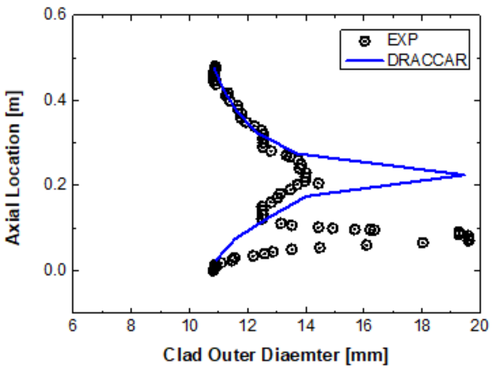

Fig. 9 Axial outer diameter of clad for IFA-650 Test No.9

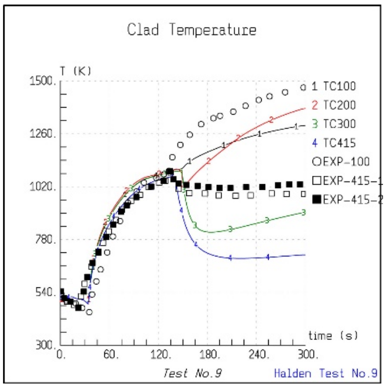

Fig. 10 The clad temperatures for IFA-650 Test No.9

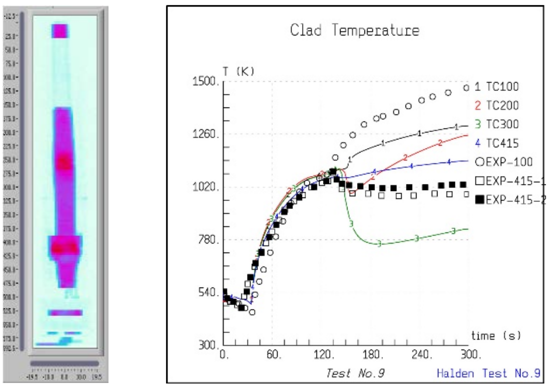

Fig. 11 Gamma scan result (left) and the clad temperatures for IFA-650 Test No.9 with ZMAX = 400mm (right)

4. Summary

Recently, the FFRD models in SPACE code are developed to response to the newly proposed ECCS rules. To compare SPACE code with the different system analysis code, several codes having FFRD model are considered. In this study, DRACCAR code, in order to analyze multi-physical phenomena, is developed with coupling mechanical / chemical / thermal-hydraulic is investigated. Using Halden IFA-650 tests, the FFRD models in the DRACCAR code are validated. In addition, sensitivity test for the various optional parameters are conducted. DRACCAR codes considered many features as input parameters. However, the physical models are not developed yet for some specific phenomena, such as deactivation of fuel relocation model in the fresh fuel condition. On the other hand, there is enough possibility to improve and develop the specific models related to FFRD phenomena using these input parameters.

ACKNOWLEDGMENT

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning(KETEP) and the Ministry of Trade, Industry & Energy(MOTIE) of the Republic of Korea (No. 20224B10200020)

REFERENCES

[1] L.O. Jernkvist and A. Massih, Models for axial relocation of fragmented and pulverized fuel pellets in distending fuel rods and its effects on fuel rod heat load, Stral Sakerhets Myndigheten SSM 2015:37, 2015.

[2] K. A. Gamble, R. J. Gardner, and R. L. Williamson, BISON FY17 Accident Capability Development L2: FMC.P15.04, CASL-U-2017-1389-000, 2017.

[3] T. Glantz, T. Taurines, O. De Luze, G. Guillard, and F. Jacq, DRACCAR: A multi-physics code for computational analysis of multi-rod ballooning, coolability and fuel relocation during LOCA transients Part one: General modeling description, Nuclear Engineering and Design, 339, pp.269-285, 2018.

[4] Belon, G. Guillard, F. Dubois, P. Girodano, V. Rouyer, DRACCAR Version 3.0 Dictionary, Rapport no. IRSN/2019-00209, 2019.

[5] Turnbull, J.A. et al., An assessment of the fuel pulverization threshold during LOCA-type temperature transients, Nuclear Science and Engineering, 179, pp. 477-485, 2015.

[6] Forgeron, T., et al., Experiment and modelling of advanced fuel rod behavior under LOCA conditions: α↔β phase transformation kinetics and EDGAR methodology, 12th International Symposium on Zirconium in the Nuclear Industry, ASTM STP 1354, pp. 256-278, 2000.