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Fuel Performance Uncertainty to Rod Burst Power in LBLOCA Analysis

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1. Introduction

Recently developed acceptance criteria of emergency core cooling system (ECCS) by Korea Institute of Nuclear Safety (KINS) has three modeling requirements, and one of the requirements deals with the consideration of fuel relocation and dispersal during loss-of-coolant accident (LOCA) [1]. And under certain conditions, zirconium alloy cladding of fuel rod can be ruptured due to the excessive plastic deformation during LOCA. And if sufficient amounts of fuel pellet were dispersed into the core, coolability can be impaired. In this safety concern, KINS has been developing a methodology to predict fuel rod burst in a core-wide during LOCA, and to support the regulation of this issue [2]. In the methodology, fuel rod power before LOCA was used as a measure for the assessment of rod burst. Also uncertainty parameters related to the performances of fuel and ECCS were identified. Fuel behaviors by combining those parameters were assessed using a statistical method. Through this process, limit curves of power to burst were derived, and fraction of fuel rod burst in APR1400 during LOCA was evaluated preliminarily.

But, authors' previous work has some limitations. One of them is that the curves and sensitivity analysis results were produced with the FRAPTRAN standalone code with the fixed thermal-hydraulic boundary conditions for the selected hot assembly. As a result, thermal-hydraulic conditions that do not reflect the actual conditions were used, which may lead to less accurate predictions. Thereby, assessment of rod burst power and sensitivity analysis by considering the actual system thermal-hydraulic behaviors is strongly required. Meanwhile, as a part of audit methodology development program for the proposed ECCS rule revision in Korea, KINS has been developing an integrated code between US Nuclear Regulatory Commission (NRC) fuel performance code, FRAPTRAN and system thermal-hydraulic code, MARS-KS [3].

In this paper, best-estimate power to burst curve was estimated with the integrated code of FRAPTRAN and MARS. And effects of fuel burst criteria and deformation model on the burst curve were also assessed. Accordingly, impacts of fuel performance uncertainty and combined uncertainty to the burst power were re-evaluated.

2. Analysis Details

2.1 Burst power analysis condition

APR1400 plant with 16x16 ZIRLO cladding fuel was used for large-break LOCA safety analysis. Design parameters of fuel rod, operating conditions, and base irradiation power history were obtained from Ref. [4]. Initial conditions of fuel rod before accident were calculated by FRAPCON-4.0 code [5], and transient fuel behaviors for a LOCA period were analyzed by the integrated code of FRAPTRAN-2.0P1 and MARS-KS1.4. Current available version of integrated code is V1129sig. It has additional models to predict the thermal behavior of fuel rod due to the formation of crud and oxide layer. And features for fuel uncertainty analysis are implemented.

For the LOCA analysis, reactor core in APR1400 was divided into a hot channel and an average channel, and a hot rod was allocated in the hot channel. Hot channel represents single hot assembly. In this study, the same linear heat generation rate (LHGR) was imposed on both the hot rod and hot assembly. This means that each rod in the hot assembly has the same LHGR. But during this process total reactor power was maintained by adjusting the power of average channel. Top-skewed cosine shape power profile was used in the analysis.

2.2 Considered factors and assessment

For the cladding burst assessment, two different cladding burst criteria are used. One is a well-known strain-based NUREG-0630 fast ramp criterion [7] and the other is a stress-based rupture criterion, which is modeled in FRAPTRAN. Two different cladding deformation models are also used. One is FRACAS-I model and the other is BALON2 model. Details of these models are described in the ref. 6. Analyzed cases with given condition are listed in Table 1. Burst curves were developed with fuel burnup from 0 to 70 MWd/kgU.

Table 1. Analysis condition for burst power in LOCA.

Case #	Deformation model	Burst criteria	LHGR Hot rod / LHGR Hot assembly
1	BALON2	NUREG-0630	1.0
2		FRAPTRAN	
3	FRACAS-I	NUREG-0630	
Ref.	BALON2		Fixed hot assembly LHGR (12.74kW/ft)

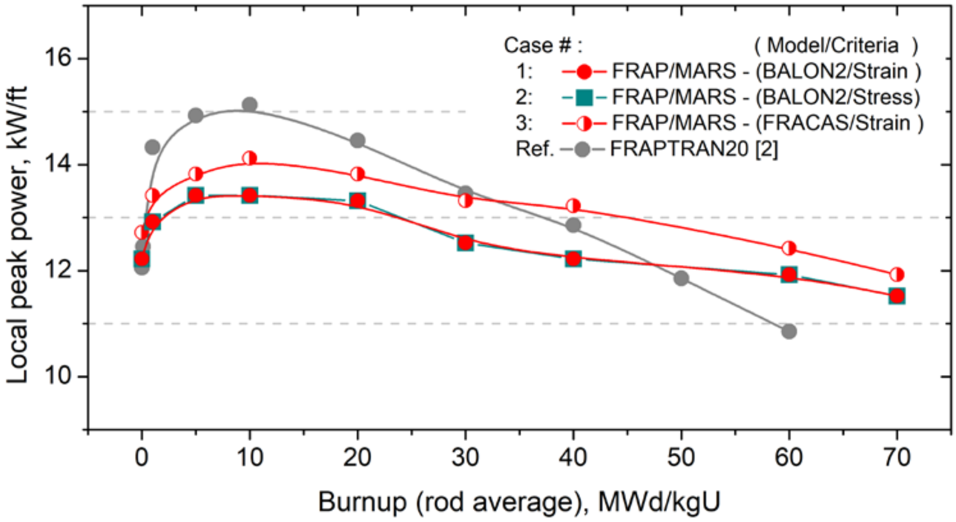

Fig. 1. Best-estimate required peak fuel power for rod burst as a function of fuel burnup with changing cladding burst criteria and deformation model

The authors have identified uncertainty parameters, such as related to the fuel rod manufacturing, to the models of computer code and thermal-hydraulics [2]. Among them, 10 and 26 parameters for manufacturing and for models of fuel rod chosen in this study. They are listed in Table 1. Impacts of these parameters to the burst power were assessed at 0 and 60 MWd/kgU fuel burnup. Root sum squared (RSS) method was used for the assessment of combined uncertainty.

3. Results and Discussion

3.1 Required fuel power for rod burst

Fig. 1 shows a peak LHGR that is required to the rod burst based on the best estimate values of the parameters as a function of fuel burnup. Here, the 'best estimate' means that the calculation was made without any tolerance or bias, listed in Table 1. As BALON2 deformation model and NUREG-0630 strain failure criterion were activated (case 1), the required burst power at 0 MWd/kgU was 12.2 kW/ft, and as burnup moved to 10 MWd/kgU, it was increased to 13.4 kw/ft. However, the burnup moved further from 10 to 70 MWd/kgU, it was reduced slowly and continuously until reaching to 11.5 kW/ft. Such a burst power evolution behavior is generally similar with the previous work [2], as shown in Fig. 1, with a little deviation. At fresh fuel condition, the required power is similar between two cases, but burnup increased to 10 MWd/kgU, the integrated code shows lower burst power than the Ref. case. And above that burnup the difference is gradually reduced, and finally even higher fuel burst power is attained above 50 MWd/kgU. These are clearly caused by the difference of hot assembly LHGR, which in turns affects the thermal-hydraulic conditions in the assembly.

Burst criteria change from strain-based NUREG-0630 to stress-based one in BALON2 model do not give any meaningful differences on burst power. As can be seen in Fig. 1, the burst power derived from stress-based criterion (case 2) is almost same as the strain-based ones (case 1). This is due to the characteristics of ballooning and burst process of the BALON2 model. Typically, when the BALON2 model was activated and deformation proceeded, the required time to reach the cladding failure strain or failure stress is very short, such as less than about 1~2 s.

Meanwhile, changing of cladding deformation model from BALON2 to FRACAS-I gives some differences. As can be seen in Fig. 1, when the FRACAS-I model was activated with the strain failure criterion (case 3), the required power was about 0.4~1.0 kW/ft higher than the BALON2 model cases (case 1, 2). This implies the selection of deformation model for burst prediction is important in the integrated code.

3.2 Influencing factors to rod burst

Table 2 shows the changes of required peak power for rod burst ($\Delta P_{\_burst}$). These changes are assessed based on the case 1 condition, listed in Table 1. In general, manufacturing uncertainties revealed a small effect to the burst power, such as less than 0.9 kW/ft. Cladding inner diameter has induced 0.9 kW/ft at zero burnup.

In model uncertainties, fuel thermal conductivity, fission gas release (FGR), cladding yield stress showed a relatively strong influence. Fuel thermal conductivity has induced 0.4 and 2.1 kW/ft at 0 and 60 MWd/kgU. At fresh fuel, FGR has no influence, but as burnup moved to 60 MWd/kgU, its impact intensified such as 1.5 kW/ft power change. Cladding yield stress showed 0.9 and 1.5 kW/ft changes at 0 and 60 MWd/kgU,

Table 2. Considered uncertainty parameters and changes of local peak power for rod burst ($\Delta P_{\_burst}$) at the fuel burnup of 0 and 60 MWd/kgU

	Parameters	**Tolerance or Bias**	**$\Delta P_{\_burst}$ (kW/ft)**			
			Case 1		**Ref.[2]**	
			0	**60**	**0**	**60**
Manufacturing	1. Cladding inner diameter (mm)	±0.04	0.9	0.1	1.3	0.3
	2. Cladding thickness (mm)	±0.04	0.2	0.2	0.6	0.6
	3. Cladding roughness (micron)	±0.3	0	0.2	0	0
	4. Pellet outer diameter (mm)	±0.013	0	0.1	0.4	0.1
	5. Pellet density (TD)(%)	±0.91	0.1	0.2	0.1	0.5
	6. Pellet re-sinter density (%)	±0.4	0.2	0.1	0	0.2
	7. Pellet roughness (micron)	±0.5	0	0.1	0	0.1
	8. Pellet dish diameter (mm)	±0.5	0.1	0.1	0.2	0.2
	9. Rod fill pressure (MPa)	±0.07	0.2	0.2	0.2	0.2
	10. Rod plenum length (mm)	±11.4	0.1	0	0	0.1
Model	11. Fuel thermal conductivity	±2σ	0.4	2.1	1	2.2
	12. Fuel thermal expansion	±2σ	0.1	0.2	0.5	0.1
	13. Fission gas release	±2σ	0	1.5	0	3
	14. Fuel swelling	±2σ	0.1	0	0	0.2
	15. Fuel relocation	±34%	0.1	0.1	0	0
	16. Fuel specific heat capacity	±1se	0.1	0.2	0	0
	17. Fuel emissivity	±1se	0	0.1	0	0
	18. Creep of cladding	±2σ	0.2	0.1	0	0.1
	19. Cladding axial growth	±2σ	0.2	0.9	0	1.2
	20. Hydrogen pickup	±2σ	0	0	0	0
	21. Cladding thermal conductivity	±2σ	0.1	0.2	0.1	0.3
	22. Cladding axial thermal expansion	±30%	0.1	0.1	0	0.2
	23. Cladding diametral thermal expansion	±30%	0.2	0.2	0	0.1
	24. Cladding elastic modulus	±1se	0.2	0.1	0	0
	25. Cladding specific heat	±1se	0.2	0	0	0
	26. Cladding yield stress	±30%	0.9	1.5	1.6	1.8
	27. Cladding surface emissivity	±1se	0	0	0	0
	28. ZrO2 thickness	±2σ	0.2	0.5	0.2	0.8
	29. ZrO2 thermal conductivity	0.4~1.6	0	0.2	0	0.8
	30. Crud thermal conductivity	0.8~1.2	0	0.2	0.1	0.1
	31. Crud thickness, micron	0~30	0.1	0	0.3	0.4
	32. Gas conductivity	±2σ	0	0.3	0	0
	33. High temperature oxidation (C-P)	±6%	0.2	0.1	0	0
	34. Radial power profile	0.9-1.0	0	0	0.1	0.2
	35. Cladding failure strain	0.2-2.0	0.1	0	0.1	0.1
	36. Decay heat	0.94-1.06	0.3	0.1	-	-
	Combined uncertainty (lower bound)		1.54 (0.78)	3.25 (1.86)	2.51 (1.24)	4.59 (2.83)

respectively. Other models showed a relatively small influence. These results indicate that the importance of each parameter is generally well coincide with the authors' previous work, listed in table 2 as Ref. case [2]. But intensity is somewhat reduced.

3.3 Combined uncertainty and further work

Table 2 also shows the results of combined fuel uncertainty (lower + upper bound) to the rod burst power evaluated by the RSS method. At fresh fuel, the combined uncertainty was 1.54 kW/ft and it was intensified as 3.25 kW/ft at 60 MWd/kgU burnup. This trend is also identified in previous work. As listed in Table 2 as ref. case, combined uncertainty at 0 and 60 MWd/kgU was 2.51 and 4.59 kW/ft, respectively. But, these values are about 1.5 times larger than the currently evaluated ones. This difference also may come from the different LHGR condition in a hot channel.

By utilizing the integrated code between FRAPTRAN and MARS, best-estimated power to burst curves depending on the analysis condition were derived. And sensitivity and combined uncertainty to were analyzed also. Through this study, similarities and differences are identified compared to the previous work. But the previous work indicated the most influencing factors are related to the thermal-hydraulic ones. Thereby identification and assessment of thermal-hydraulics uncertainty in details, and combining these with current work are required for constructing the final power to burst curves.

4. Summary

Best-estimate fuel power for rod burst and effect of fuel performance uncertainty to the burst power were evaluated by the integrated code of FRAPTRAN and MARS-KS. Following results can be drawn.

- Best-estimated fuel power for rod burst is affected by cladding deformation model of BALON2 and FRACAS-I. BALON2 results in conservative values. However, cladding burst criteria such as the strain-based NUREG-0630 and stress-based FRAPTRAN have no effects on the burst power within this analysis condition.
- Among 36 fuel performance uncertainty parameters, fuel thermal conductivity, fission gas release, clad yield stress showed relatively strong impacts on the burst power. As fuel burnup increased, fuel performance uncertainty to the burst power becomes stronger.
- In general, the present analysis of fuel performance uncertainty to the burst power were similar with the results of FRAPTRAN standalone case. But some differences exist, and these are mostly come from the difference of thermal-hydraulic conditions.

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REFERENCES

[1] Joosuk Lee et. al., “Research on the ECCS Acceptance Criteria Revision for Domestic PWR Plants”, KINS/RR-1848, 2018.11

[2] Joosk Lee and Young-Seok Bang, “Development of Evaluation Methodology of Core-Wide Fuel Rod Burst in LOCA Safety Analysis”, TopFuel 2019, Sep.22-26, Seattle Washington, USA

[3] Joosuk Lee at.al., “Validation of Fuel/Thermal-Hydraulics Coupled Computer Code and Development of Fuel Models”, KINS/RR-1849 Vol.2, 2019.11

[4] KEPCO-NF, “PLUS7 Fuel Design and Safety Evaluation for Korean Standard Nuclear Power Plants”, Propriety, KNF-TR-DMR-04001/N/A Rev.0, 2006.

[5] K.J. Geelhood et. al., “FRAPCON-4.0: A Computer Code for the Calculation of Steady-State, Thermal-Mechanical Behavior of Oxide Fuel Rods for High Burnup”, PNNL-19418, Vol.1. Rev.2, September 2015.

[6] K.J. Geelhood et. al., “FRAPTRAN-2.0: A Computer Code for the Transient Analysis of Oxide Fuel Rods”, May 2016, PNNL-19400, Vol.1. Rev2.

[7] D.A. Power, R.O. Meyer, “Cladding Swelling and Rupture Models for LOCA Analysis”, April 1980 NUREG-0630