Transactions of the Korean Nuclear Society Autumn Meeting
Yeosu, Korea, October 25-26, 2018

Factors Affecting Fuel Rod Burst in LOCA Safety Analysis

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1. Introduction

For the period of loss-of-coolant accident (LOCA), fuel rod can be ruptured due to the excessive plastic deformation of zirconium alloy cladding at high temperature. This deformation and rupture process is typically called as ballooning and burst. Main driving force of rod burst is attributed to the pressure difference between rod internal and coolant. And rod internal pressure can be affected by many factors related to the fuel rod uncertainty. If ballooning and burst happens, there is a possibility that fragmented fuel pellets can be dispersed into the core [1]. And if sufficient amount of fuel pellets dispersed combined with significant fuel deformation, coolability can be impaired. Thereby evaluation of fuel rod burst in a core-wide during LOCA is necessary for the assurance of core coolability.

In this paper, factors affecting fuel rod burst related to fuel uncertainty are evaluated and their combined effects are preliminarily assessed within licensing fuel burnup.

2. Analysis Details

2.1 LOCA analysis condition

APR1400 PWR plant with 16x16 ZIRLO cladding fuel was used for LOCA safety analysis. Design parameters of fuel rod, operating conditions, and base irradiation power history were obtained from Ref. [2]. Initial conditions of fuel rod before accident were calculated by FRAPCON-4.0 code [3], and transient fuel behaviors for a LOCA period were analyzed by FRAPTRAN-2.0KS code. FRAPTRAN-2.0KS is a modified version of FRAPTRAN-2.0 [4] in KINS for the implementation of crud and oxide layer in fuel rod.

Thermal-hydraulic boundary conditions such as heat transfer coefficient, pressure and temperature of coolant for a LOCA period were obtained from APR1400 LBLOCA safety analysis at the fuel burnup of 30MWd/kgU. Detailed information on the analysis can be found in authors' previous work [5].

2.2 Considered factors and assessment

Total 36 uncertainty parameters related to the fuel rod manufacturing and models of computer code were considered. These are listed in Table 1. In manufacturing uncertainties, 10 different parameters were used. And 26 parameters were considered in model uncertainties. Basis of the given uncertainty in each parameter can be found in Ref. [6]. In this work, heat transfer coefficient of coolant is selected as an additional parameter with ±25 % uncertainty assumption.

Impacts of uncertainty parameters to the required peak fuel power for rod burst were assessed from 0 to 60 MWd/kgU fuel burnup. For the cladding burst assessment, a well-known strain-based NUREG-0630 fast ramp criterion was adapted.

Statistical approaches such as the root sum squared (RSS) method and simple random sampling (SRS) technique were used for the assessment of lower bound of peak fuel power. Total 6,000 inputs were produced with the uncertainty combinations by the SRS.

3. Results

3.1 Required fuel power for rod burst

Fig. 1 shows a best-estimate required peak fuel power for rod burst as a function of fuel burnup. At zero burnup, the required power was 9.9 kW/ft, and burnup increased slightly to 1 MWd/kgU, it changed to 11.8 kw/ft. And fuel burnup moved to 5~10 MWd/kgU, it reached about 12.5 kW/ft. Then, the peak power reduced continuously from 12.5 to 9.3 kW/ft as burnup changed from 10 to 60 MWd/kgU.

3.2 Influencing factors to rod burst

Table 1 shows the changes of peak power of rod burst ($\Delta P_{\_burst}$). In general, manufacturing uncertainties revealed a small influence on burst power,

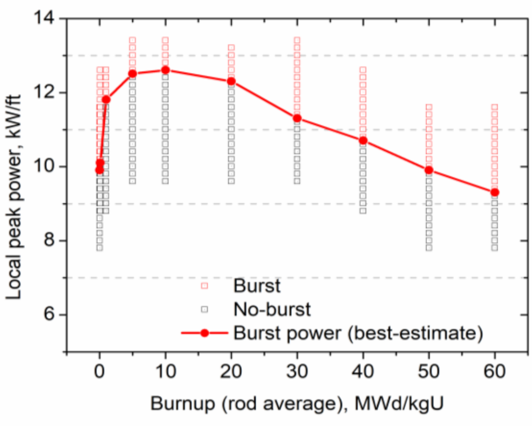

Fig. 1. Best-estimate required peak fuel power for rod burst as a function of fuel burnup.

such as less than 0.5 kW/ft. But cladding inner diameter and thickness have induced a moderate influence such as up to ~1.1 kW/ft.

In model uncertainties, fission gas release (FGR), cladding yield stress and heat transfer coefficient of coolant showed a strong influence. At fresh and low burnup fuel, FGR has a little influence. But as fuel burnup moved to medium to high, its impact gradually intensified. And finally 2.6 kW/ft power change was observed at 60 MWd/kgU burnup. Cladding yield stress showed about 2.5~2.9 kW/ft power changes except for fresh fuel. Heat transfer coefficient of coolant showed a predominant influence. It induced 2.5~4.3 kW/ft power changes within prescribed uncertainty. Fuel thermal conductivity showed a moderate influence, such as 0.7~1.4 kW/ft. Other models showed a relatively small influence.

3.3 Combined uncertainty and bounding power

Fig. 2 shows the results of combined uncertainty to the rod burst evaluated by the SRS approach. The results revealed that total 1,186 samples among 6,000 were counted as burst. Many bursted samples were observed below the best-estimate peak power curve. Fig. 2 also shows the lower bound of peak power for rod burst that is evaluated by the RSS technique. At fresh fuel, the lower bound was 7.8 kW/ft and it increased to 9.5~9.7 kW/ft with burnup moved to 5~10 MWd/kgU. Then the lower bounds were reduced gradually with burnup increase. At 60 MWd/kgU burnup the lower bound was 6.2 kW/ft. Analysis results showed that the lower bound curve could envelop the bursted samples successfully even if some samples were out of bound. More investigations are still required to prescribe the lower bound curve.

3.4 Further research

Analysis results of peak power for rod burst shown in Fig. 1, 2 seem to be more or less conservative because they used hot channel thermal-hydraulics boundary conditions. Thereby, further assessments are still required by considering following factors.

- Reflecting actual thermal-hydraulics boundary conditions (heat transfer coefficient, pressure, temperature) and their uncertainties
- Effects of axial power profiles of fuel rod with burnup change
- Statistical treatment for the evaluation of lower bound curve
- etc.

Table 1. Considered uncertainty parameters and changes of local peak power for rod burst ($\Delta P_{\_burst}$) at the given fuel burnup (MWd/kgU)

	Parameters	**Tolerance or Bias**	**ΔP_{burst} (kW/ft), 0**	**5**	**10**	**20**	**30**	**40**	**60**
Manufacturing	1. Cladding inner diameter (mm)	±0.04	0.9	0.8	0.9	0.6	0.8	0.5	0.4
	2. Cladding thickness (mm)	±0.04	0.4	0.7	0.7	0.9	1.1	0.7	0.7
	3. Cladding roughness (micron)	±0.3	0.0	0.0	0.0	0.0	0.1	0.0	0.1
	4. Pellet outer diameter (mm)	±0.013	0.2	0.3	0.3	0.2	0.1	0.2	0.1
	5. Pellet density (TD)(%)	±0.91	0.1	0.1	0.1	0.2	0.4	0.3	0.4
	6. Pellet re-sinter density (%)	±0.4	0.0	0.0	0.0	0.2	0.2	0.1	0.0
	7. Pellet roughness (micron)	±0.5	0.0	0.0	0.0	0.0	0.0	0.1	0.2
	8. Pellet dish diameter (mm)	±0.5	0.2	0.3	0.3	0.3	0.3	0.4	0.1
	9. Rod fill pressure (MPa)	±0.07	0.2	0.3	0.3	0.3	0.2	0.2	0.2
	10. Rod plenum length (mm)	±11.4	0.0	0.1	0.0	0.0	0.1	0.0	0.1
Model	11. Fuel thermal conductivity	±2σ	0.8	0.7	0.7	1.1	0.8	1.2	1.4
	12. Fuel thermal expansion	±2σ	0.4	0.3	0.2	0.0	0.2	0.1	0.1
	13. Fission gas release	±2σ	0.0	0.0	0.2	1.0	1.7	2.4	2.6
	14. Fuel swelling	±2σ	0.0	0.0	0.0	0.0	0.1	0.1	0.1
	15. Fuel relocation	±34%	0.0	0.1	0.0	0.2	0.2	0.1	0.0
	16. Fuel specific heat capacity	±1se	0.0	0.0	0.0	0.0	0.1	0.1	0.1
	17. Fuel emissivity	±1se	0.0	0.0	0.0	0.0	0.2	0.1	0.1
	18. Creep of cladding	±2σ	0.0	0.1	0.1	0.2	0.1	0.0	0.1
	19. Cladding axial growth	±2σ	0.0	0.0	0.0	0.2	0.3	0.7	0.9
	20. Hydrogen pickup	±2σ	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	21. Cladding thermal conductivity	±2σ	0.0	0.1	0.0	0.1	0.1	0.3	0.3
	22. Cladding axial thermal expansion	±30%	0.0	0.1	0.0	0.0	0.1	0.1	0.1
	23. Cladding diametral thermal expansion	±30%	0.0	0.1	0.0	0.0	0.1	0.1	0.2
	24. Cladding elastic modulus	±1se	0.0	0.1	0.0	0.0	0.2	0.0	0.3
	25. Cladding specific heat	±1se	0.0	0.1	0.0	0.0	0.2	0.1	0.1
	26. Cladding yield stress	±30%	1.5	2.7	2.8	2.8	2.9	2.9	2.5
	27. Cladding surface emissivity	±1se	0.0	0.1	0.0	0.0	0.1	0.1	0.1
	28. ZrO2 thickness	±2σ	0.2	0.1	0.1	0.4	0.6	0.6	0.7
	29. ZrO2 thermal conductivity	0.4~1.6	0.0	0.0	0.1	0.1	0.2	0.3	0.5
	30. Crud thermal conductivity	0.8~1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	31. Crud thickness, micron	0~30	0.2	0.1	0.2	0.3	0.1	0.1	0.2
	32. Gas conductivity (He)	±2σ	0.2	0.1	0.0	0.1	0.1	0.1	0.0
	33. High temperature oxidation (C-P)	±6%	0.0	0.0	0.0	0.0	0.1	0.0	0.0
	34. Cladding failure strain	0.2~2.0	0.7	0.1	0.0	0.1	0.0	0.1	0.6
	35. Heat transfer coefficient of coolant	0.75~1.25	2.9	4.3	4.3	3.8	3.4	3.1	2.5
	36. Radial power profile	0.9~1.1	0.1	0.1	0.0	0.0	0.2	0.1	0.1

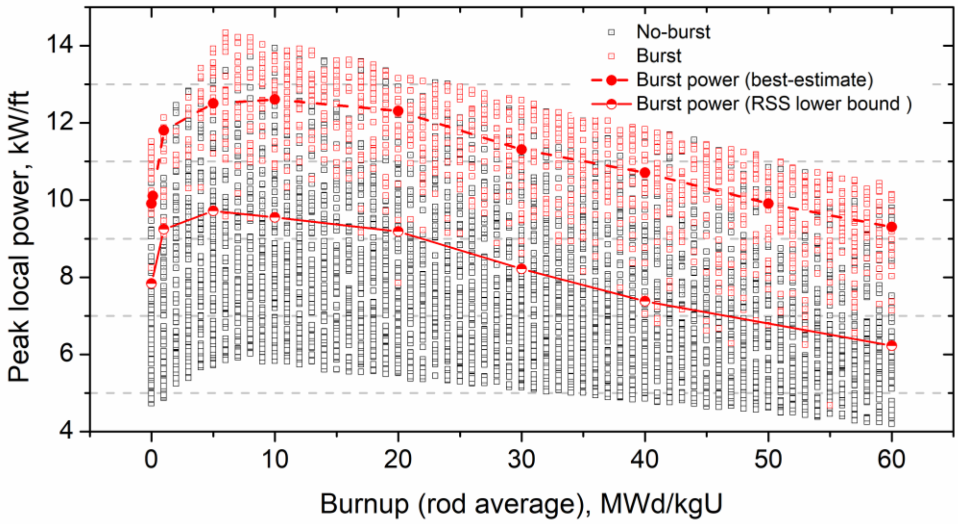

Fig. 2. Preliminary assessment of rod burst power with combined uncertainty and lower bound of power curve within licensing fuel burnup of 60 MWd/kgU.

4. Summary

Factors affecting fuel rod burst and their combined effects were evaluated. Following results can be drawn preliminarily.

- Required peak power for rod burst varied with fuel burnup. Maximum power was observed at 5~10 MWd/kgU burnup, and it reduced continuously with burnup increase.
- Manufacturing uncertainty showed a little or moderate influence on peak power for rod burst. But related to the model uncertainty, particularly heat transfer coefficient of coolant, fission gas release and clad yield stress showed significant impacts.
- Root sum squared (RSS) approach seemed to be reasonable for the assessment of lower bound power for rod burst. But for the exact statistical statement more investigations are still required.

ACKNOWLEGEMENT

The preparation of this paper was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KOFONS), granted financial resource from the Nuclear Safety and Security Commission (NSSC), Republic of Korea (No. 1805004-0118-SB110).

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