Effect of Fuel Rod Uncertainty on ECR Change of Zirconium Alloy

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1. Introduction

In 1996, a fuel-cladding research program was initiated by NRC that is intended to investigate the behavior of high-exposure fuel cladding under loss of coolant accident (LOCA) conditions [1]. The research results revealed that hydrogen, which is absorbed into the cladding during the burnup-related corrosion process under normal operation, has a significant influence on embrittlement during a hypothetical LOCA. When that cladding is exposed to high-temperature LOCA conditions, the elevated hydrogen levels increase the solubility of oxygen in the beta phase and the rate of diffusion of oxygen into the beta phase. Thus, embrittlement of cladding in a highly corroded cladding with significant hydrogen pickup can occur below the current safety limit, 17% equivalent cladding reacted (ECR).

For these reasons, draft ECCS acceptance criteria (10 CFR 50.46c) proposed by USNRC [1, 2] have called, through the draft of regulatory guide DG-1263, for the establishment of analytical limits on peak cladding temperature and integral time at temperature that correspond to the measured ductile-to-brittle transition for the zirconium-alloy cladding material. The ductile-to-brittle threshold defined in Fig.1 is an acceptable analytical limit on integral time at temperature as calculated in local oxidation calculations using the Cathcart-Pawel (CP) correlation. This analytical limit is acceptable for the zirconium-alloy cladding materials tested in the NRC's LOCA research program, which were Zry-2, Zry-4, ZIRLO™, and M5.

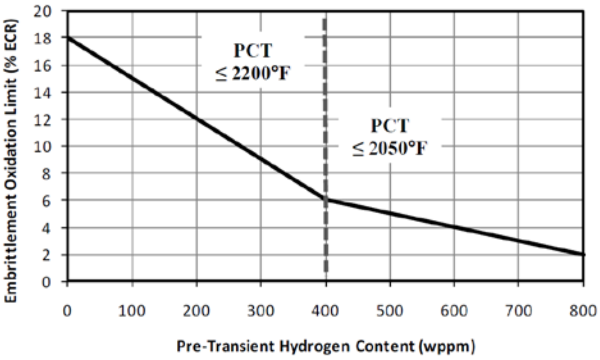

Fig.1: An acceptable analytical limit on peak cladding temperature and integral time at temperature (as calculated in local oxidation calculations using the CP correlation) [1].

As shown in the Fig.1, the allowable ECR is a function of hydrogen content, margin assessment has to be done within the licensing fuel burnup. Therefore, in this study, as a first step, sensitivity analysis has been performed to identify which uncertainty parameter of fuel rod is important to the ECR change under LOCA condition. And effect of combined uncertainty is also assessed utilizing a root sum of square method.

2. Method

2.1 Base case specifications

The operation conditions and the design parameters of the utilized Westinghouse-type fuel with Zircaloy-4 cladding are listed in Table 1. They are obtained from the NUREG-1754 [3].

Applied bounding power history was that the linear heat rate (LHR) of 10.18kW/ft (rod average) was maintained up to 30 MWd/kgU fuel burnup, and it was reduced continuously. Applied peak LHR before LOCA initiation was 14.2kW/ft. For the fuel performance assessment, FRAPCON-3.4a and FRAPTRAN-1.5 code were used that can evaluate the thermo-mechanical performance of fuel rod during steady-state and transient condition, respectively. Two different fuel burnup such as 0.5 and 30 MWd/kgU were assumed before LOCA initiation.

Utilized thermal-hydraulic boundary conditions were obtained by RELAP5 system code in a typical Westinghouse 3-loop plant with the assumption of 100% reactor power and 7% steam generator tube plugging.

2.2 Combined uncertainty analysis

The combined uncertainty is evaluated using root of sum of squares (RSS) method, represented as follows.

$$P = P_{base} + Root\left(\sum_i (P_i - P_{base})^2\right)$$

where:

- ΔP: The combined uncertainty effect of all parameters.
- P_{base}: ECR value of the base model.
- P_i: ECR value after changing a parameter.

This method will show the combined effect of fuel rod uncertainty to the change of ECR.

Table 1: Design parameters of fuel rod and operational conditions [3].

Parameter (unit)	
Cladding material	Zircaloy-4
Cladding inner diameter(mm)	8.18
Cladding thickness(mm)	0.61
Cladding roughness(μm)	0.5
Pellet outer diameter(mm)	8
Pellet density (TD) (%)	95
Pellet re-sinter density (%)	0.9
Pellet roughness(μm)	2
Pellet dish diameter & depth (mm)	4.01, 0.287
Rod fill pressure (MPa)	2.41
Rod plenum length (mm)	254
Active fuel length (m)	3.66
Mass flowrate(kg/m^2)	12.47 x 10^6
Coolant inlet temperature (^{o}C)	288
System coolant pressure (MPa)	15.5
Pitch (mm)	12.6

But, for the clear assessment of effects of fuel rod uncertainty on the ECR change, heat transfer coefficients during LOCA transient are reduced about 55% with respect to the base case.

3. Identification of Fuel Rod Uncertainty

3.1 Manufacturing uncertainties

Table 2 shows the considered manufacturing parameters and their uncertainties. The manufacturing uncertainties represent an average value of the tolerances [3]. In this study, 10 different parameters such as cladding inner diameter, cladding thickness, cladding roughness, pellet diameter, pellet density, pellet re-sinter density, pellet roughness, pellet dish diameter and depth, rod fill gas pressure and rod plenum length were considered and their tolerances were obtained from the NUREG/CR-7001.

3.2 Model uncertainties

Table 2 also lists the considered model uncertainties. The model uncertainties represent the difference between the model and experimental data [3]. Among them, Pacific Northwest National Laboratory has modeled already the uncertainties of fuel thermal conductivity, fuel thermal expansion, fission gas release (FGR), fuel swelling, cladding creep, cladding axial growth, cladding corrosion, cladding hydrogen uptake in FRAPCON-3.4a code. Uncertainties of the models such as cladding thermal conductivity, cladding elastic modulus, fuel and cladding specific heat, fuel and cladding emissivity, fission gas and zirconia (ZrO_2) thermal conductivity were set based on the information from NUREG/CR-7024. Among them, uncertainties of cladding elastic modulus, fuel and cladding specific heat, fuel and cladding emissivity were set as ±1 standard error (±1se) because within those uncertainty ranges they revealed sufficient data coverage. Uncertainty of zirconia thermal conductivity was set as−50%/+10%.

Uncertainties of thermal expansion and yield stress of Zircaloy cladding were set as ±30% according to the information of NUREG/CR-7001. Also, uncertainty of cladding failure stress and strain was set as −30 MPa/+90MPa and −80%/+60%, respectively, based on the NUREG/CR-7023. Uncertainty of high temperature zirconium oxidation model (Cathcart-Powel model) was set as ±6% based on the ORNL/NUREG-17.

3.3 Power uncertainties

The power uncertainties represent the difference of fuel power between the measurement and the real power [3]. Table 2 shows the considered power uncertainty parameters. Uncertainty of fuel power during steady-state operation was set as ±2%. Uncertainty of decay heat was set as ±6.6%. These uncertainties are come from the audit calculation methodology of KINS-REM.

4. Analysis Results

4.1 Sensitivity due to each uncertainty parameter

According to the base case analysis with reduced heat transfer coefficients during LOCA, the assessed ECR is 2.15 and 5.18% at the fuel burnup of 0.5 and 30 MWd/kgU, respectively. With this information, sensitivity analysis has been carried out.

Table 2 shows the deviation of equivalent cladding reacted (ΔECR) from the base case due to the uncertainty parameters of fuel rod. Manufacturing uncertainties show that the cladding inner diameter has the relatively strong impact on ΔECR at 0.5 MWd/kgU fuel burnup. It results in 1.45% ΔECR. Fuel pellet diameter, rod fill pressure and plenum length show a similar levels of impact. They result in about 0.46% ΔECR. Meanwhile at 30 MWd/kgU burnup the cladding outer diameter and pellet roughness reveal about 1% ΔECR.

In case of model uncertainties, in turn, fuel thermal expansion, cladding corrosion and crud thickness have the most significant influence. They result in about 2~2.7% ΔECR at the fuel burnup of 0.5 MWd/kgU, while, fuel thermal conductivity and fuel relocation show about 1% ΔECR. At 30 MWd/kgU fuel burnup, the most dominant parameters are cladding corrosion and fuel thermal conductivity. They induced about 4% ΔECR. Impacts of other parameters in model uncertainties are relatively small such as less than 1% ΔECR.

The impacts of power uncertainties are not significant at both fuel burnups. ΔECR is less than 1%, but decay heat has induced more strong influence than the power has done.

Table 2: Sensitivity analysis results and their effect on the change of equivalent cladding reacted (ΔECR).

		Range of Uncertainty	Reference for Uncertainty	0.5 MWd/kgU			30 MWd/kgU		
				ECR (Upper)	ECR (Lower)	ΔECR%	ECR (Upper)	ECR (Lower)	ΔECR%
Manufacturing	1. Cladding inner diameter, mm	±0.04	NUREG/CR- 7001	3.74	2.28	1.45	5.20	5.18	0.02
	2. Cladding outer diameter, mm	±0.04	“	2.33	2.40	0.07	4.72	5.75	1.03
	3. Cladding roughness, micron	±0.3	“	2.15	2.15	0.00	5.24	5.14	0.09
	4. Pellet diameter, mm	±0.013	“	2.25	2.71	0.46	5.24	5.25	0.02
	5. Pellet density (TD), %	±0.91	“	2.11	2.20	0.09	2.04	5.35	0.31
	6. Pellet re-sinter density, %	±0.4	“	2.14	2.17	0.03	5.16	5.23	0.08
	7. Pellet roughness, micron	±0.5	“	2.15	2.15	0.00	5.27	4.31	0.96
	8. Pellet dish diameter, mm	±0.5	“	2.15	2.15	0.01	5.18	5.22	0.04
	9. Rod fill pressure, MPa	±0.07	“	2.61	2.14	0.46	5.20	5.20	0.01
	10. Rod plenum length, mm	±11.4	“	2.60	2.15	0.45	5.21	5.19	0.02
Model (including physical and mechanical properties	11. Fuel thermal conductivity	±2σ	NUREG/CR- 7024	2.43	3.58	1.15	4.14	7.86	3.72
	12. Fuel thermal expansion	±2σ	“	2.53	5.23	2.71	5.19	5.18	0.00
	13. Fission gas release (FGR)	±2σ	“	2.15	2.15	0.00	5.37	5.07	0.29
	14. Fuel swelling	±2σ	“	2.15	2.15	0.00	5.21	5.18	0.02
	15. Fuel relocation	±34%	NUREG/CR- 3907	1.97	2.90	0.93	5.19	5.19	0.01
	16. Fuel specific heat capacity	±1se	NUREG/CR- 7024	2.16	2.14	0.02	5.2	5.17	0.04
	17. Fuel emissivity	±1se	“	2.15	2.15	0.00	5.18	5.19	0.00
	18. Cladding corrosion (oxide thickness)	±2σ	“	4.17	2.17	2.00	8.30	4.13	4.17
	19. Creep of cladding	±2σ	“	2.11	2.20	0.09	5.19	5.19	0.01
	20. Cladding axial growth	±2σ	“	2.15	2.15	0.00	5.19	5.18	0.01
	21. Cladding hydrogen pickup	±2σ	“	2.15	2.15	0.00	5.18	5.18	0.00
	22. Cladding thermal conductivity	±2σ	“	2.12	2.19	0.08	5.11	4.43	0.67
	23. Cladding axial thermal expansion	±30%	NUREG/CR- 7001	2.15	2.15	0.00	5.19	4.36	0.83
	24. Cladding diametral thermal expansion	±30%	“	2.26	2.87	0.61	5.32	5.18	0.03
	25. Cladding elastic modulus	±1se	NUREG/CR- 7024	3.11	2.49	0.62	5.24	5.18	0.05
	26. Cladding specific heat	±1se	“	2.06	2.27	0.21	5.05	5.35	0.30
	27. Cladding yield stress	±30%	NUREG/CR- 7001	2.15	2.15	0.00	5.18	5.19	0.01
	28. Cladding surface emissivity	±1se	NUREG/CR- 7024	2.15	2.15	0.01	5.18	5.19	0.00
	29. Zirconium oxide thermal conductivity	−50%/ +10%	“	2.15	2.15	0.00	5.16	5.45	0.29
	30. Gas conductivity (He)	±2σ	“	2.13	2.17	0.04	5.18	4.36	0.82
	31. Cladding failure stress, MPa	−30 ~ +90	NUREG/CR- 7023	2.15	2.15	0.00	5.18	5.18	0.00
	32. Cladding failure strain	−80%/ +60%	“	2.15	2.15	0.00	5.18	5.18	0.00
	33. High temperature oxidation (C-P)	±6%	ORNL/NUREG- 17	2.22	2.08	0.14	5.28	5.08	0.20
	34. Crud thermal conductivity	±50%	Assumption	2.82	3.35	0.53	5.50	6.21	0.71
	35. Crud thickness, micron	0 ~ 30	Assumption	4.77	2.15	2.62	5.92	5.18	0.74
Power	36. Power (LCO)	±2%	KINS-REM	2.24	2.07	0.17	5.41	4.99	0.42
	37. Decay heat, %	±6.6%	“	2.50	1.86	0.63	5.69	4.77	0.92
Base case					2.15			5.18	
RSS Root ($\Sigma_i (P_i\text{-}P_{be})^2$)					5.42			4.40	

4.2 Combined uncertainty results – RSS Approach

Analysis results of combined uncertainty to the ΔECR are also listed in Table 2. Evaluated ΔECR is 5.42 and 4.40% at the fuel burnup of 0.5 and 30 MWd/kgU, respectively. This indicates that as fuel burnup moves up to the 30 MWd/kgU, effect of fuel rod uncertainty to the ΔECR is somewhat reduced. This appears due to the utilization of protective high temperature oxidation model in C-P correlation and the use of very low heat transfer coefficients during LOCA. Therefore as the different analysis conditions are used the results may change.

5. Conclusions

The influence of fuel rod uncertainty to the change of equivalent cladding reacted (ΔECR) has been evaluated with 0.5 and 30 MWd/kgU fuel burnup. Utilized codes are FRAPCON-3.4a and FRAPTRAN-1.5. Main results are as follows.

- The important uncertainty parameters the ΔECR are mainly related to the model. While manufacturing and power uncertainties show a relatively small impact.
- In model uncertainties, fuel thermal conductivity, fuel thermal expansion, cladding corrosion and crud thickness reveal a strong influence. But the importance is changed when fuel burnup increases.
- Combined uncertainty analysis reveals that the ΔECR at the fuel burnup of 30 MWd/kgU is somewhat reduced as fuel burnup moves from 0.5 to 30 MWd/kgU.

These results are valid at the given analysis condition in this paper. Therefore, if the analysis environments are changed, for instance, the use of non-protective oxide model in FRAPTRAN inputs, the results may be changed.

REFERENCES

[1] Draft Regulatory Guide DG-1263, Establishing Analytical Limits for Zirconium-based Alloy Cladding, U.S. Nuclear Regulatory Commission, March 2014

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