Sensitivity and Uncertainty Analysis on the Fuel Rod Performance based on Statistical Method

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1. Introduction

In regulatory point of view, important parameters of fuel rod performance, such as rod internal gas pressure, peak fuel centerline temperature, cladding hoop strain, oxide thickness, hydrogen uptake can be affected by several uncertainties which are related to the initial dimension of fuel rod, models in computer code, and operating conditions. Those uncertainties are readily categorized by three types; manufacturing, model and power uncertainties[1]. In this study, we have assessed what uncertainties will have an inpact on the rod performance, and also have assessed preliminarily the combined effects of uncertainties by using a statistical method based on non-parametric order statistics approach[2].

2. Analysis Details

Fuel rod performance up to 53 MWd/kgU was analyzed by use of FRPACON-3.4a audit code. The base case employed in this study utilized a 17x17 PWR fuel with Zircaloy-4 cladding, and the detailed information of rod dimension, power history and operating conditions can be found in Ref. [1]. AOO power pulse was prescribed such that the output power was increased 50% for a period of 4hrs at the fuel burnup of 30 MWd/kgU. Manufacturing, model and power uncertainties were listed in Table 1. Manufacturing uncertainties represent an average value of the tolerances. Model uncertainties were set as $\pm 2\sigma$ (standard deviation). Power uncertainties include steady state, AOO power pulse and duration of AOO. Sampling probability within each uncertainty parameter was assumed as normal distribution except for duration of AOO pulse.

Total 153 inputs were produced with the uncertainty combinations, by the simple random sampling (SRS) technique [3]. As 153 runs have been performed, the forth largest values can be used as rod performance estimation with upper tolerance limit of 95% probability and 95% confidence level [4].

3. Results

3.1 Sensitivity due to each uncertainty parameter

Table 2 shows the impacts of each uncertainty on the rod performance with respect to the base case, within prescribed tolerance and bias ranges, listed in Table 1. In general, manufacturing uncertainties revealed a relatively small influence on the performance parameters, such a less than about 5%. But cladding inner diameter and thickness have induced 12.92 and 14.63 % changes of rod internal pressure and hydrogen uptake, respectively. In case of model uncertainties, some of them have very significant effects on the performance. For example, fuel thermal conductivity showed the most predominant influence on internal pressure, centerline temperature and cladding hoop strain, resulting in values that differ from the base cases by as much as 54.9%. Rod internal pressure, oxide thickness and hoop strain were also strongly affected by fission gas release (FGR), cladding corrosion and fuel thermal expansion model, respectively. Steady state and AOO power uncertainties showed a moderate influence on the outputs of interest.

3.2 Combined uncertainties to the rod performance

Fig.1 shows the frequency count of maximum fuel centerline temperature and cladding strain increment evaluated by uncertainty combinations. Maximum fuel temperature varied from 2334.6 to 2833.3K, and 4th order largest value was 2778.8 K. This value is larger than the base case about 185 K, but it is still lower than the design limit of fuel melting temperature.

Table 1. Considered manufacturing, model and power uncertainties to the rod performance analysis

		Base	Tolerance or Bias	Probability distribution
Manufacturing	Cladding ID, mm	8.18	±0.04	Normal
	Cladding thickness, mm	0.610	±0.04	Normal
	Cladding roughness, microns	0.5	±0.3	Normal
	Pellet OD, mm	8.0	±0.013	Normal
	Pellet density(TD), %	95	±0.91	Normal
	Pellet re-sinter density, %	0.9	±0.4	Normal
	Pellet roughness, microns	2.0	±0.5	Normal
	Pellet dish diameter & depth, mm	4.01, 0.287	±0.5, +0.05	Normal
	Rod fill pressure, MPa	2.41	±0.07	Normal
	Rod plenum length, mm	254	±11.4	Normal
Model	Fuel thermal conductivity	0	$\pm 2\sigma$	Normal
	Fuel thermal expansion	0	$\pm 2\sigma$	Normal
	FGR	0	$\pm 2\sigma$	Normal
	Cladding corrosion	0	$\pm 2\sigma$	Normal
	Fuel swelling	0	$\pm 2\sigma$	Normal
	Creep of cladding	0	$\pm 2\sigma$	Normal
	Cladding axial growth	0	$\pm 2\sigma$	Normal
	H pickup	0	$\pm 2\sigma$	Normal
Power	Power(steady state), %	100	±2	Normal
	Power(AOO), %	150	±3	Normal
	Duration of AOO pulse, hr	4	±1	Uniform

Table 2. Impact on rod performance parameters due to the uncertainty of individual parameter.

		Rod internal pressure	Oxide thickness	Hydrogen uptake	Fuel centerline temp. at AOO	ΔHoop strain at AOO
Deviation from base case		Δ %	Δ %	Δ %	Δ %	Δ %
Manufacturing	Cladding ID	11.92	0.00	6.27	0.43	0.89
	Cladding thickness	1.01	1.87	14.63	0.64	1.77
	Cladding roughness	0.43	0.00	0.00	0.46	1.30
	Pellet OD	2.84	0.16	0.17	0.01	0.34
	Pellet density(TD)	6.03	0.62	0.64	2.00	3.99
	Pellet re-sinter density	3.47	0.00	0.00	0.87	1.78
	Pellet roughness	0.91	0.00	0.00	0.78	2.28
	Pellet dish diameter & depth	1.08	0.00	0.00	0.03	3.41
	Rod fill pressure	3.65	0.00	0.00	0.07	0.20
	Rod plenum length	5.20	0.00	0.00	0.04	0.17
Model	Fuel thermal conductivity	51.46	0.00	0.00	22.74	45.26
	Fuel thermal expansion	3.03	0.00	0.00	0.05	36.88
	FGR	47.87	0.00	0.00	0.85	0.75
	Cladding corrosion	6.24	79.49	5.62	2.07	5.86
	Fuel swelling	0.71	0.00	0.00	0.01	0.03
	Creep of cladding	1.34	0.00	0.00	0.01	0.05
	Cladding axial growth	7.46	0.00	0.00	0.02	0.03
	H pickup	0.00	0.00	26.60	0.00	0.00
Powe r	Power(steady state)	8.29	1.16	1.19	-	-
	Power(AOO)	-	-	-	3.07	13.32
	Duration of AOO pulse	-	-	-	0.14	0.73

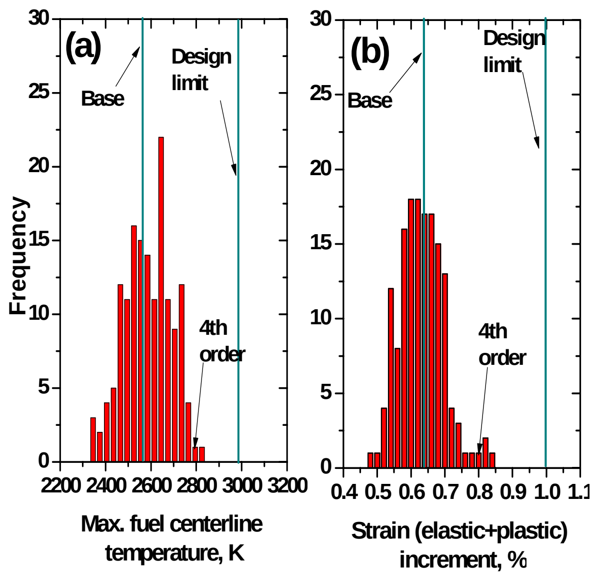

Fig. 1. Frequency count of (a) maximum fuel centerline temperature and (b) cladding strain increment during AOO

Due to the uncertainty combination, strain (elastic + plastic) increment during AOO ranged from 0.489 to 0.833%, and 4^{th} order largest value was 0.805 %. This value is larger than the base case about 0.165 %, but 0.195% strain margin still exists to the strain design limit, 1%.

4. Summary

Based on the sensitivity and uncertainty studies to the rod performance parameters, the following results can be drawn.

- Sensitivity studies indicated that manufacturing and power uncertainties have a little or moderate influence on the rod performance parameters. But related to the model, particularly fuel thermal conductivity model, showed significant impact on the rod performance.
- Preliminary analysis results of the combined uncertainties to the rod performance parameters by the well-known statistical method were reasonable, but followings should be considered further.
    - Uncertainty ranges and probability distribution function (especially power and model)
    - Model uncertainties (such as mechanical properties of cladding, oxide conductivity, crud model etc.)

REFERENCES

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