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An Approach for Quantifying Safety Margins in Nuclear Power Plants

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1. Introduction

The objective of this research is to apply the safety margin quantification methodology proposed by Garvrilas et. al.[1] for important plant operational modifications such as power uprate and to evaluate the effect of such modifications to safety margins represented by plant metrics including peak cladding temperature, reactor coolant system pressure and etc. The safety metrics were obtained using RELAP5 for the event scenarios in event tree of reference plant. The plant parameters were obtained by frequency-weighted safety indices for individual event scenarios into aggregate indices. Pilot application of proposed method was performed for Kori-3,4 nuclear unit for which the safety and other analysis are being performed regarding power uprate. The insights from pilot application were presented in this paper.

2. Barrier Damage States and Safety Indices

Safety indices are numerical answers to safety questions[1]. Regarding the barrier integrity, several limits can be defined as below;

- Normal operation limit
- Regulatory acceptance limit
- Barrier disruption limit
- Barrier loss of function limit

For peak cladding temperature, 2200°F and 17% cladding oxidation is the regulatory acceptance limit in the loss of coolant accident. The minimum distance between calculated peak cladding temperature and regulatory acceptance limit can be defined as acceptance index, i_{accept}. Gavrilas et. al. defined four safety indices as illustrated in Figure 1.

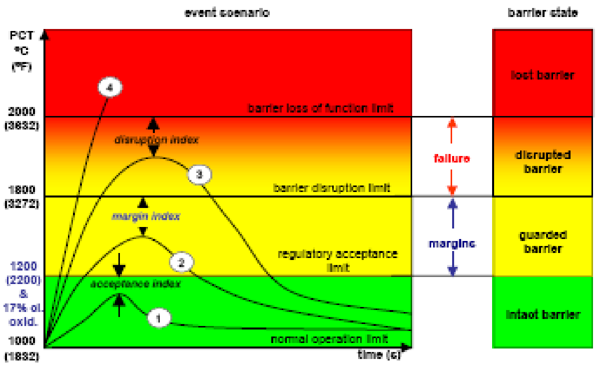

Figure 1. The impact of safety parameter trajectory on barrier damage state (from reference 1)

Normalized safety indices such as acceptance index between acceptance limit and operational limit is given by;

$$
\begin{aligned}
&i_{accept} = 1, \text{ for OL} > f(t)_{max} \\
&i_{accept} = \frac{AL - f(t)_{\max}}{AL - OL}, \text{ for OL} < f(t)_{max} < \text{AL} \qquad (1) \\
&i_{accept} = 0, \text{ for } f(t)_{max\,x} > \text{AL}
\end{aligned}
$$

where $f(t)$ is the function describing the parameter trajectory, OL is the normal operation limit and AL is the regulatory acceptance limit. $f(t)_{max}$ is the maximum value of the safety parameter along the trajectory. For margin and disruption indices, barrier disruption limit(DL) and barrier loss limit(LL) were used instead of AL in this paper.

3. Plant Safety Metrics

3.1 Aggregate Index

When safety indices are calculated for all safety-significant event scenarios, the frequency of each event scenarios are reflected as weighting function to safety indices. The aggregate plant indices as plant safety metrics can be calculated as below;

$$\bar{i}^{B}_{mi} = \frac{\sum_{allevents}\left(h_j \cdot \left(\bar{i}^{B}_{mi}\right)_j\right)}{\sum_{allevents} h_j} = \sum_{allevents}\left[\left(\frac{h_j}{\sum_{allevents} h_j}\right)\cdot\left(\bar{i}^{B}_{mi}\right)_j\right] = \sum_{allevents}\left(\hat{h}_j \cdot \left(\bar{i}^{B}_{mi}\right)_j\right) \qquad (2)$$

where $\bar{i}^{B}_{mi}$ is the aggregate barrier margin index, h_j is the frequency of occurrence of event j, and $\hat{h}_j$ is normalized frequency of occurrence of event j over all events under consideration.

3.2 Global Safety Index

To consider the respective importance to the safety inquiries, weighting factors were introduced and the sum of all weighted indices is defined as global safety index and it is expressed as below;

$$I = w_1 \Delta\breve{\bar{t}}_1 + w_2 \Delta\breve{\bar{t}}_2 + \cdots + w_{N-1}\Delta\breve{\bar{i}}_{N-1} + w_N \Delta\breve{\bar{i}}_N \qquad (3)$$

where $\breve{\bar{i}}$'s and $\Delta\breve{\bar{t}}$'s are modified aggregate safety and temporal indices, and w's are their respective weight fractions for the N safety inquiries.

4. Example Application to Kori-3,4 Power Uprate

4.1 Event Identification

Proposed methodology was applied to Kori-3,4 power uprate case where 4.5% of power uprate was considered. The initiating event chosen was small-break LOCA and the event scenarios were presented in event tree shown in Figure 2[2].

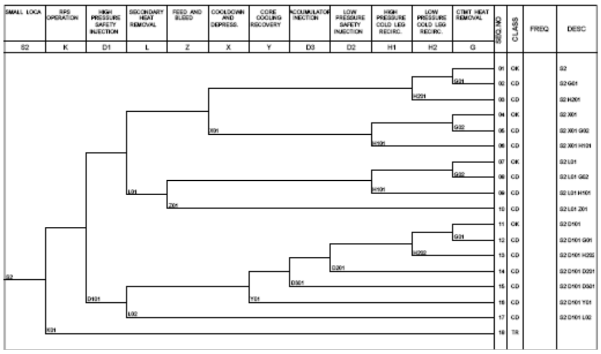

Figure 2. Kori-3,4 Small-Break LOCA Event Tree

For SBLOCA of Kori-3,4 event, frequency of each sequence was identified as presented in Table 1. Also, the peak cladding temperatures and RCS pressures for base case(100% power) and uprated power(104.5%) were presented in Table 1. Peak cladding temperature and RCS pressure were calculated using RELAP5.

Table 1. Event Frequencies and Event Parameters

Seq. No.	Frequency	State	PCT Base (°C)	PCT Uprate (°C)	Pressure Base (psia)	Pressure Uprate (psia)
1	4.98E-04	margin	614.665	666.022	2269.232	2268.956
2	3.80E-10	CD*	>2000	>2000	2269.232	2268.956
3	1.32E-06	CD	1677.8	1735.2	2269.232	2268.956
4	1.72E-08	margin	614.665	666.022	2269.232	2268.956
5	1.00E-12	CD	>2000	>2000	2269.232	2268.956
6	4.85E-08	CD	>2000	>2000	2269.232	2268.956
7	7.92E-08	margin	614.665	666.022	2269.232	2268.956
8	1.00E-12	CD	>2000	1870	2269.232	2268.956
9	1.43E-12	CD	1441.4	1497.8	2269.232	2268.956
10	1.19E-11	CD	>2000	>2000	2269.232	2268.956
11	1.52E-07	margin	797.8	884.161	2269.232	2268.956
12	1.00E-12	CD	>2000	>2000	2269.232	2268.956
13	6.04E-11	CD	>2000	>2000	2269.232	2268.956
14	5.81E-08	CD	>2000	>2000	2269.232	2268.956
15	1.00E-12	CD	>2000	>2000	2269.232	2268.956
16	1.80E-10	CD	>2000	>2000	2269.232	2268.956
17	1.36E-09	CD	>2000	>2000	2269.232	2268.956
Tot	5.00E-04					

* CD means core damage state.

4.2 Limit Definition

Normal operation limit, regulatory acceptance limit, barrier disruption limit, barrier loss of function limit for peak cladding temperature and reactor coolant system pressure were defined as shown in Table 2. For RCS pressure, normal operation and regulatory acceptance limits were defined only.

Table 2. Limit Definition for Example Application

Limit Description	PCT (°C)	Pressure (psia)	Remark
Barrier loss of function limit	2000	-	Barrier Loss Limit (LL)
Barrier disruption	1800	-	Disruption Limit (DL)
Regulatory acceptance	1200	3200	Acceptance Limit (AL)
Normal operation	390*	2250	Operational Limit (OL)

* PCT operational limit was roughly estimated from the average operation temperature 370°C (700°F) and minimum DNBR ratio 1.3.

4.3 Safety Index and Aggregate Index Calculation

Based on the parameters in Table 1, safety indices for peak cladding temperature and RCS pressure were calculation for base and uprate cases respectively and results are shown in Table 3. Frequency-weighted indices for base and uprate cases were presented in Table 4. Aggregate indices were calculated using equation (3) and result was shown in Table 5.

Table 3. Safety Index for Base and Uprate Cases

Seq. No.	Base Case				Uprate Case			
	$i_{PCT, accept}$	$i_{PCT, margin}$	$i_{PCT, disrupt}$	$i_{P,accept}$	$i_{PCT, accept}$	$i_{PCT, margin}$	$i_{PCT, disrupt}$	$i_{P,accept}$
1	0.7226	0.8407	0.8605	0.9798	0.6592	0.8042	0.8286	0.9800
2	0.0	0.0	0.0	0.9798	0.0	0.0	0.0	0.9800
3	0.0	0.0867	0.2001	0.9798	0.0	0.0460	0.1645	0.9800
4	0.7226	0.8407	0.8605	0.9798	0.6592	0.8042	0.8286	0.9800
5	0.0	0.0	0.0	0.9798	0.0	0.0	0.0	0.9800
6	0.0	0.0	0.0	0.9798	0.0	0.0	0.0	0.9800
7	0.7226	0.8407	0.8605	0.9798	0.6592	0.8042	0.8286	0.9800
8	0.0	0.0	0.0	0.9798	0.0	0.0	0.0	0.9800
9	0.0	0.2543	0.3407	0.9798	0.0	0.2143	0.3119	0.9800
10	0.0	0.0	0.0	0.9798	0.0	0.0	0.0	0.9800
11	0.4965	0.7108	0.7467	0.9798	0.3899	0.6495	0.6931	0.9800
12	0.0	0.0	0.0	0.9798	0.0	0.0	0.0	0.9800
13	0.0	0.0	0.0	0.9798	0.0	0.0	0.0	0.9800
14	0.0	0.0	0.0	0.9798	0.0	0.0	0.0	0.9800
15	0.0	0.0	0.0	0.9798	0.0	0.0	0.0	0.9800
16	0.0	0.0	0.0	0.9798	0.0	0.0	0.0	0.9800
17	0.0	0.0	0.0	0.9798	0.0	0.0	0.0	0.9800

Table 4. Frequency-weighted Index for Base and Uprate Cases

Seq. No.	Base Case				Uprate Case			
	$i_{PCT, accept}$	$i_{PCT, margin}$	$i_{PCT, disrupt}$	$i_{P,accept}$	$i_{PCT, accept}$	$i_{PCT, margin}$	$i_{PCT, disrupt}$	$i_{P,accept}$
1	1.38E-04	7.93E-05	6.95E-05	1.01E-05	1.70E-04	9.75E-05	8.54E-05	9.94E-06
2	3.80E-10	3.80E-10	3.80E-10	7.69E-12	3.80E-10	3.80E-10	3.80E-10	7.58E-12
3	1.32E-06	1.21E-06	1.06E-06	2.67E-08	1.32E-06	1.26E-06	1.10E-06	2.63E-08
4	4.77E-09	2.74E-09	2.40E-09	3.48E-10	5.86E-09	3.37E-09	2.95E-09	3.43E-10
5	1.00E-12	1.00E-12	9.24E-13	2.02E-14	1.00E-12	1.00E-12	1.00E-12	2.00E-14
6	4.85E-08	4.85E-08	4.85E-08	9.82E-10	4.85E-08	4.85E-08	4.85E-08	9.68E-10
7	2.20E-08	1.26E-08	1.10E-08	1.60E-09	2.70E-08	1.55E-08	1.36E-08	1.58E-09
8	1.00E-12	1.00E-12	1.00E-12	2.02E-14	1.00E-12	1.00E-12	1.00E-12	2.00E-14
9	1.43E-12	1.07E-12	9.34E-13	2.89E-14	1.43E-12	1.12E-12	9.84E-13	2.85E-14
10	1.19E-11	1.19E-11	1.19E-11	2.41E-13	1.19E-11	1.19E-11	1.19E-11	2.37E-13
11	7.65E-08	4.40E-08	3.85E-08	3.08E-09	9.27E-08	5.33E-08	4.67E-08	3.03E-09
12	1.00E-12	1.00E-12	1.00E-12	2.02E-14	1.00E-12	1.00E-12	1.00E-12	2.00E-14
13	6.04E-11	6.04E-11	6.04E-11	1.22E-12	6.04E-11	6.04E-11	6.04E-11	1.21E-12
14	5.81E-08	5.81E-08	5.81E-08	1.18E-09	5.81E-08	5.81E-08	5.81E-08	1.16E-09
15	1.80E-10	1.80E-10	1.80E-10	2.02E-14	1.80E-10	1.80E-10	1.80E-10	2.00E-14
16	1.80E-10	1.80E-10	1.80E-10	3.64E-12	1.80E-10	1.80E-10	1.80E-10	3.59E-12
17	1.36E-09	1.36E-09	1.36E-09	2.75E-11	1.36E-09	1.36E-09	1.36E-09	2.71E-11

Table 5. Aggregate Indices

Safety Index	Base	Uprate	Comments
Disruption	0.8585	0.8266	disruption margin is reduced
Margin	0.8384	0.8020	margin is reduced
Acceptance	0.7205	0.6573	acceptable margin is reduced

5. Conclusion

Through the pilot application of safety margin quantification methodology proposed by Garvrilas et. al. to Kori-3,4 power uprate case, following insights were derived.

- All margins for power uprate case were reduced compared to base case.
- The most impacting case is the end state change from marginal state to core damage state in power uprate case. Such cases affect the safety indices and aggregate indices mostly.
- Limit definition and core damage definition in PSA can impact the safety indices.
- For core damage sequences, the escalation indices can impact the safety index calculation.

REFERENCES

[1] Garvrilas et. al., "A Generalized Framework for Quantifying Safety Margins in Nuclear Power Plants," Draft Report, Nov. 2004

[2] KHNP, Kori 3/4 Probabilistic Safety Assessment Final Report, June 2003