Reliability Engineering and System Safety 129 (2014) 19–28

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

# Application of risk informed safety margin characterization to extended power uprate analysis

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ARTICLE INFO

*Article history:*
Received 17 October 2013
Received in revised form
15 April 2014
Accepted 19 April 2014
Available online 2 May 2014

*Keywords:*
Risk-informed decision-making
Safety margins
Probabilistic risk assessment
Extended power uprate

ABSTRACT

In this paper we present some initial results of the application of a risk-informed safety margin characterization (RISMC) approach to the analysis of the impact of an extended power uprate (EPU) on plant safety for selected transient and accident sequences. These initial applications were conducted to demonstrate the feasibility and practicality of using the RISMC approach to analyze the safety impact of EPUs at both a pressurized water reactor (PWR) and a boiling water reactor (BWR). For the PWR application, the analysis focused on the loss of main feedwater (LOMFW) event with failure of auxiliary feedwater (AFW) where feed and bleed (F&B) cooling is required to prevent core damage. For the BWR case study, station blackout (SBO) sequences leading to core damage were analyzed. A consistent and repeatable process was developed and applied to identify those key parameters that would be analyzed. Distributions were constructed to represent the uncertainties associated with each of the key parameters. These distributions were sampled using a Latin Hypercube Sampling (LHS) technique to generate sets of sample cases that were used in the physics simulation runs using the MAAP4 code. Simulation results were evaluated to determine the changes to safety margins which would occur due to the uprated power conditions; the results obtained were then compared to those for the current nominal full power. The results obtained indicate, as expected, that safety margins may be reduced with increases in plant power level. However, for most power uprate levels, these safety margin reductions were found to be small. A limited study of margin recovery strategies was performed for the PWR case that indicated that minor to moderate changes in plant operation or design could be used to recover the safety margin reduction that would occur from the power uprate.

## 1. Safety margin characterization framework

As described in earlier EPRI sponsored studies [1–5], the original design and licensing of commercial nuclear power plants (NPPs) ensured adequate safety margins by performing conservative engineering analyses and applying conservative judgment to specify appropriate safety limits for critical plant parameters. Maintenance of these safety margins has served as a foundational principle of plant operation and regulation since the advent of commercial nuclear power. However, as NPP lifetimes are extended beyond the initial approved license duration, and operational enhancements (such as EPUs) are made to achieve enhanced economic performance, there has developed a critical need to develop and apply an approach to evaluate and manage safety margins that is both technically justifiable and economical to implement. Additionally, since the accident at the Fukushima Dai-ichi plant, a renewed focus on NPP safety analysis throughout the world is likely to increase the need to more systematically and comprehensively evaluate the impact of plant long-term operation (LTO) decisions on safety margins. These factors increase the need for a methodology that can be economically applied by licensees and can generate results that can be readily reviewed by regulatory personnel.

To address this need, ongoing research has been performed to develop and demonstrate risk-informed approaches to evaluate and characterize NPP safety margins. The basic framework is represented conceptually by the relationship

$$P(C > L)$$

which depicts the evaluation of a parameter (represented by a load $L$) versus an acceptance guideline (represented by a capacity $C$). Stated a different way, one is concerned with determining what is the probability that the load experienced during a particular analyzed event does not exceed the capacity to handle it? Although, in practice, this assessment has generally been simplified to the

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http://dx.doi.org/10.1016/j.ress.2014.04.008

## Acronyms

| | |
|---|---|
| AAC | alternate AC |
| AC | alternating current |
| AFW | auxiliary feedwater |
| AGR | advanced gas reactor |
| ALARA | as low as reasonably achievable |
| BWR | boiling water reactor |
| CCDP | conditional core damage probability |
| CCP | centrifugal charging pump |
| CD | core damage |
| CDF | core damage frequency |
| CST | condensate storage tank |
| ECCS | emergency core cooling system |
| EDG | emergency diesel generator |
| EF | error factor |
| EPRI | Electric Power Research Institute |
| EPU | extended power uprate |
| ERG | emergency response guideline |
| ESF | emergency safeguards feature |
| FOM | figure of merit |
| FV | Fussell–Vesely |
| F&B | feed and bleed cooling |
| HCTL | heat capacity temperature limit |
| HEP | human error probability |
| HPCI | high pressure coolant injection |
| HPI | high pressure injection |
| HPSW | high pressure service water |
| LER | licensee event report |
| LERF | large early release frequency |
| LHS | Latin hypercube sampling |
| LOMFW | loss of main feedwater |
| LOOP | loss of offsite power |
| LR | large release |
| LTO | long-term operation |
| LWR | light water reactor |
| MAAP | modular accident analysis program |
| NPP | nuclear power plant |
| PCPL | primary containment pressure limit |
| PCT | peak cladding temperature |
| PI | plant impact |
| PORV | power operated relief valve |
| PRA | probabilistic risk assessment |
| PTS | pressurized thermal shock |
| PWR | pressurized water reactor |
| RCIC | reactor core isolation cooling |
| RCP | reactor coolant pump |
| RISMC | risk informed safety margin characterization |
| RPV | reactor pressure vessel |
| SBO | station blackout |
| SDP | significance determination process |
| SG | steam generator |
| SORV | stuck-open safety relief valve |
| SSC | structures, systems and components |
| TAF | top of active fuel |
| T–H | thermal–hydraulic |
| UQ | uncertainty quantification |
| US | United States |

comparison of point estimate values, in reality these parameters are more accurately represented as distributions that account for the uncertainties associated with prediction of both the load and capacity. Fig. 1 conceptually illustrates the relationship between a calculated load (e.g., temperature, pressure, etc.) distribution and the capacity distribution for a structure, system or component (SSC). In this paradigm the concept of "margin" is transformed from a simple "distance" between the point estimates of the load and capacity to that of a probability that the load experienced will exceed the installed capacity to handle it. In this figure we also indicate how various aspects of NPP LTO could impact these margins over time by shifting or modifying the underlying load/capacity distributions. Note that a more complete discussion of safety margins, the potential impact of extended NPP operation on them, and prior foundational research on the RISMC approach is discussed in detail in previous EPRI research [1].

In the research described in [2], the approach to characterizing the safety margins was specified as follows:

- "Load" assessment: Utilize an applicable systems code (which for the purposes of the demonstrations described in this paper was the MAAP4 code) to parametrically investigate the input parameters and their influence on one or more key outputs (e.g., peak core temperature, fraction of core with peak cladding temperature greater than some defined limit, etc.). To support these analyses, the bases for sensitive input parameter values were reviewed and an applicable distribution for each representative parameter was developed.
- "Capacity" assessment: Select key output parameters to be investigated. Review the technical bases for parameter acceptance guidelines and assign a distribution to the "capacity" limits.

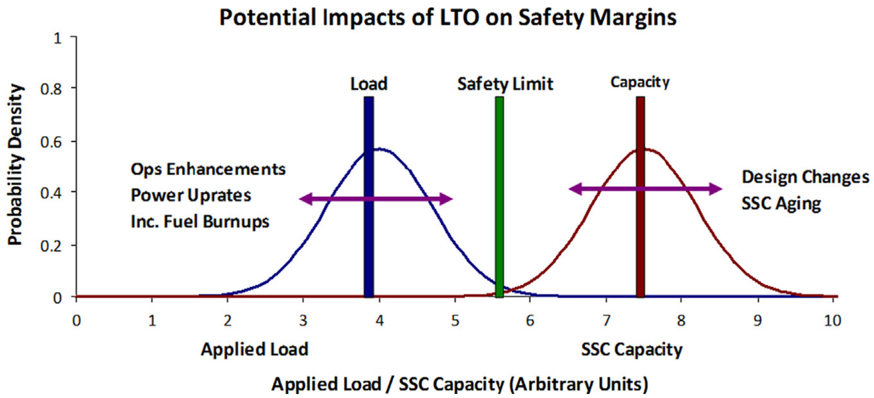

**Fig. 1.** Probability that SSC capacity exceeds load – $P(C>L)$ – and potential impact of NPP LTO on safety margins [5].