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Pilot application of risk informed safety margin characterization to a total loss of feedwater event

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ABSTRACT

In this paper we present the results of application of a risk-informed safety margin characterization (RISMC) approach to the analysis of a loss of feedwater (LOFW) event at a pressurized water reactor (PWR). This application considered a LOFW event with the failure of auxiliary feedwater (AFW) for which feed and bleed cooling would be required to prevent core damage. For this analysis the main parameters which impact core damage for the scenario were identified and probability distributions were constructed to represent the uncertainties associated with the parameter values. These distributions were sampled using a Latin Hypercube Sampling (LHS) technique to generate sets of sample cases to simulate using the MAAP4 code. Simulation results were evaluated to determine the safety margins relative to those obtained using typical probabilistic risk assessment (PRA) modeling (success criteria) assumptions.

1. Safety margin characterization framework

1.1. Introduction

The original design and licensing of commercial nuclear power plants (NPPs) ensured that adequate safety margins were designed and maintained by conducting conservative engineering analyses and applying conservative judgment in specifying 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 licensing periods and operational enhancements (such as extended power uprates) are made to achieve enhanced economic performance, questions logically arise with respect to whether the plant's safety margins will remain adequate. Thus, there is a critical need to develop and apply an approach to evaluate and manage safety margins in a manner that is both technically justifiable and economical to implement [1].

To address this need, the Electric Power Research Institute (EPRI) is sponsoring research into the development of risk informed approaches to evaluate and characterize NPP safety margins.

The basic framework is represented conceptually by the relationship of the probability (P) that the load (L) experienced by the plant (for a critical plant safety parameter) would be below the plant's capacity (C) to withstand the load during some postulated event, represented symbolically as

$$P(C \geq L)$$

Fig. 1 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 thus characterized as the probability that the load experienced will be less than the installed capacity to handle it.

However, during the design and licensing of the current fleet of commercial NPPs, actual data from which estimates of the actual capacities and loads for plant SSCs could be developed were either not available or considered to be too expensive to obtain. Thus, an alternative approach was devised to ensure sufficient safety margins were built into the plant design and operational framework and against which regulatory assessments could be conducted. First, plant design specifications were required to be very conservative from an engineering perspective. This design conservatism resulted in utilizing SSCs that are capable of performing at levels that are significantly higher than what is required to support normal operation, anticipated plant transients or postulated design basis accidents. The second element of the approach addressed the issue from an operational perspective by specifying “hard” safety limits which were set at a level that was significantly below the designed system capacity. This concept is shown schematically in Fig. 2. From a licensing perspective, these margins are specified by placing regulatory limits on plant parameters that

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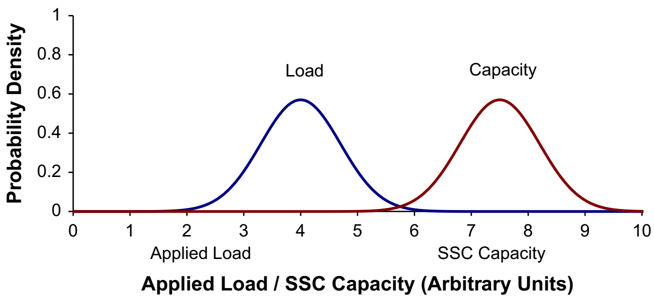

Fig. 1. Safety margin concept.

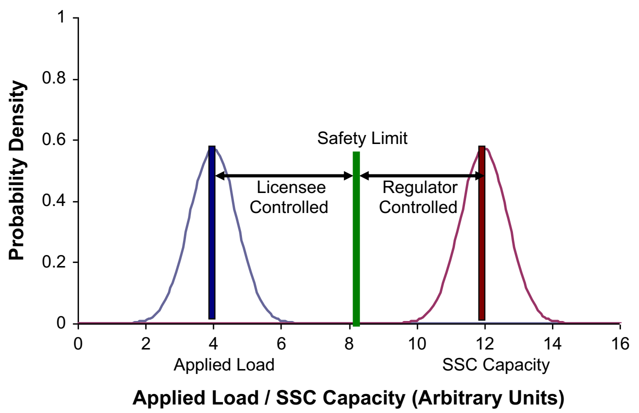

Fig. 2. Safety margin concept applied to NPP licensing (from [4,6]). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

are considered to be important to ensuring nuclear safety; in particular plant parameters that, if not exceeded, provide assurance that the principle barriers to fission product release (i.e. the fuel cladding, the reactor vessel and primary system piping, and the containment) successfully will perform their intended functions. In the United States regulatory system, these limits are specified either in federal regulations (e.g. Title 10—Code of Federal Regulations) directly or are specified in the plant Technical Specifications [2].

Over time, however, NPP operation has the potential to impact the original design margins. This can be reflected by changes in the expected values or the shapes of the distribution functions associated with the load, capacity or both. For example, ageing of plant materials can result in decreased resiliency of the system to withstand perturbations; thus causing the capacity curve to shift to the left (from that shown in Fig. 1). Additionally, changes made to enhance plant operations or economics also can impact safety margins. For example, increased fuel burnups and plant power uprates can result in operation of plant SSCs at higher stress levels (i.e. closer to their design tolerances) and shift the load curve to the right. However, we should note that not all actions taken will necessarily result in decreases to the original safety margins. For example, some pressurized water reactor (PWR) plants have installed dedicated reactor coolant pump (RCP) seal injection systems. For these plants the likelihood of an RCP seal loss of coolant accident is greatly reduced and thus the margins are enhanced by such a modification. As another example, improved analytical methods and supporting operational data can provide improved estimates of actual SSC performance; thus shifting the expected value of the load curve to the left. As a final example, the implementation of diagnostic condition based maintenance activities (such as vibration monitoring or lubricating oil analysis) can provide an effective means of identifying degraded conditions of rotating equipment at an early stage. As a result, these technologies can influence the actual safety margins by decreasing the variance of the distribution of the load function; thus providing a higher degree of confidence that safety margins are being appropriately maintained [2].

As previously discussed, enhancements being implemented by NPP operators to achieve enhanced or extended plant operation have the potential to impact the safety margins that were specified in the plant's original licensing basis. This situation is complicated by the possibility that, although an individual design or operational change may not result in a significant erosion of any safety margin, the cumulative effect of multiple changes may result in a challenge to them. As a result of this potential, regulatory authorities have included consideration of the potential impact on safety margins as part of their reviews of significant operational changes or license extensions. We note that it is important to recognize that the business case for decisions related to significant changes to plant operation necessarily involves other considerations. In addition to the evaluation of margins from the traditional safety viewpoint, the business case evaluation also needs to consider a much broader class of issues. For the actual decision for a NPP operator to pursue any significant change in plant operation (including extended operating lifetime, power uprate, or fuel cycle extension), the decision to implement such a change typically is dominated by a detailed evaluation of the economic implications of the proposed change. Thus, satisfying nuclear safety requirements specified by the governing regulatory authority will not necessarily assure a successful economic outcome. As a particularly critical example, uncertainties in the understanding of long-term plant behavior may be highly significant in the sense that they can have a major impact on the decision to make the major investment associated with a significant enhancement or plant license extension. Thus, having a framework for addressing these uncertainties could be of tremendous value to the relevant decision-makers. Because the structure for conducting a risk informed approach to characterizing safety margins that we describe in this paper is quite general, we propose that it has the potential to be used to address a broader range of issues to support NPP decision making [3].

1.2. Current state of RISMC research

As a response to the possibility of NPPs extending their operational lifetimes, the Nuclear Energy Agency Committee on the Safety of Nuclear Installations (NEA/CSNI) formed a working group to evaluate the potential impacts of NPP life extension, aging, and operational changes on plant safety margins. This task group consisted of senior personnel responsible for nuclear safety technology representing regulatory authorities from several nations (Czech Republic, Finland, France, Germany Japan, Mexico, Republic of Korea, Slovenia, Spain, Switzerland, and the United States). This group published their final report on development of a Safety Margins Action Plan (SMAP) [4] that was intended to address five critical activities for consideration in regulatory assessment and decision making. The identified activities were to:

(a) Develop a working definition of safety margins and related concepts.
(b) Develop a process for the assessment of plant safety margins.
(c) Identify appropriate methods for conducting safety margin evaluations.
(d) Identify methods for safety margin quantification.
(e) Prepare a CSNI guidance document on safety margins for use by NPP regulatory authorities.

To permit a comprehensive assessment of NPP safety margins, the SMAP Task Group developed an integrated structure for the identification and analysis of applicable safety margins. The approach