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Risk-Informed Safety Margin Characterization (RISMC): Integrated Treatment of Aleatory and Epistemic Uncertainty in Safety Analysis

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ABSTRACT

The concept of “margin” has a long history in nuclear licensing and in the codification of good engineering practices. However, some traditional applications of “margin” have been carried out for surrogate scenarios (such as design basis scenarios), without regard to the actual frequencies of those scenarios, and have been carried out in a systematically conservative fashion. In the RISMC project, which is part of the Department of Energy’s “Light Water Reactor Sustainability Program” (LWRSP), we are developing a risk-informed characterization of safety margin. Beginning with the traditional discussion of “margin” in terms of a “load” (a physical challenge to system or component function) and a “capacity” (the capability of that system or component to accommodate the challenge), we are developing the capability to characterize probabilistic load and capacity spectra, reflecting both aleatory and epistemic uncertainty in system response. For example, the probabilistic load spectrum will reflect the frequency of challenges of a particular severity. Such a characterization is required if decision-making is to be informed optimally. However, in order to enable the quantification of probabilistic load spectra, existing analysis capability needs to be extended. Accordingly, the Idaho National Laboratory (INL) is working on a next-generation safety analysis capability whose design will allow for much more efficient parameter uncertainty analysis, and will enable a much better integration of reliability-related and phenomenology-related aspects of margin.

KEYWORDS

Margin, risk-informed, safety analysis, uncertainty

1. INTRODUCTION

This paper describes the current formulation of the “Risk-Informed Safety Margin Characterization” (RISMC) pathway within the US Department of Energy’s “Light Water Reactor Sustainability (LWRS) Program” [1] with special emphasis on the integrated treatment of aleatory and epistemic uncertainty. In this paper, it is argued that the decision-making needs foreseen within the LWRS program call for fundamental improvements over existing analysis capability: that the decision-making needs call for a state-of-knowledge characterization of reactor safety margin that is not obtainable from currently available analysis tools.

US nuclear plant owners need to make investment decisions as their plants approach the end of their extended operating licenses (that is, as the plants approach the end of their renewed license terms), decisions that go well beyond regulatory concerns. These decisions include whether to seek an additional license renewal (beyond the first renewal), and/or whether

particular systems, structures, or components (SSCs) need refurbishment or replacement. For United States Nuclear Regulatory Commission (NRC) purposes, the license renewal rule allows for the possibility of additional license renewals, based on the existing application review process, which considers SSCs whose performance bears on NRC decisions. This license renewal process will provide reasonable assurance of adequate protection of the public through extended license periods; but it will not provide plant owners with assurance of future economical operation, for several reasons. The concerns of nuclear plant owners go well beyond licensing-basis SSCs, and even for those SSCs, plant economics may be affected by scenarios that do not threaten the public. Plant decision-making therefore depends on analysis having a level and scope that go beyond the analysis considered adequate for regulatory needs.

In order to provide focus to the analysis, and to help communicate its results to the decision-makers, considerable stress is being placed on the idea of “margin” as a unifying concept. Essentially all key issues can be analyzed and discussed in terms of a suitably generalized concept of “margin.” The idea of “margin” has been used for a long time in diverse contexts, but recent years have seen a broadening of the concept, and this broader concept is what is needed for the present application.

In order to work with this broader concept of margin, it will be necessary to achieve fundamental improvements in reactor analysis capability. This paper discusses the broader concept of margin, and shows what improvements in analysis capability will be needed in order to work with it. Section 2 discusses the applicable concepts of “margin” and “risk-informed,” while Section 3 relates these concepts to analysis needs.

2. RISK-INFORMED SAFETY MARGIN

2.1 Margin

We begin with the following dictionary definition [2]:

Margin:

Something that is over and above what is strictly necessary and that is designed to provide for emergencies: a spare amount of measure or degree allowed or given for contingencies or special situations: a factor or group of factors making for ready opportunity or ample scope or personal choice in proceeding freely

This paper will use the terms “load” and “capacity” in a general sense to refer (respectively) to the magnitude and nature of the physical challenge imposed on an SSC by a class of scenarios, and the capability of the SSC to withstand a given challenge. For example, if “load” is acceleration during an earthquake, an SSC’s “capacity” is the ability of that SSC to withstand that acceleration without failing. The probability of failure is then simply the probability that load exceeds capacity, or $P(L > C)$, as suggested in Figure 1 below.

The above dictionary definition of “margin” does not use the terms “load” and “capacity,” but implicitly contains the idea that margin is related to the spare amount of measure or degree of capacity in the context of the loads that are foreseen or foreseeable. It captures the idea that if significant margin is present, then there is a reduced probability of load exceeding capacity,

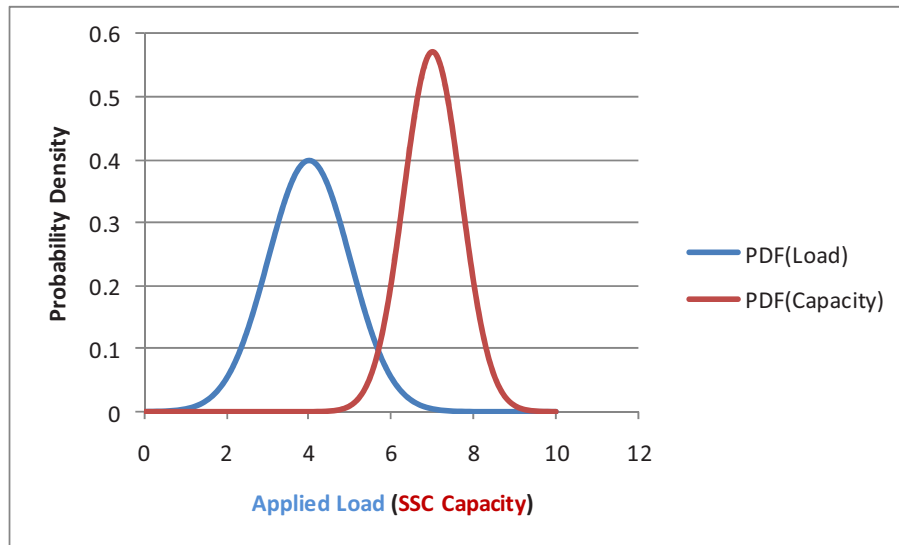


Figure 1. Notional “Load” and “Capacity”

and the decision-maker has more freedom to proceed. The dictionary definition likewise does not contain the term “uncertainty,” and appears not to contemplate state-of-knowledge uncertainty; but it explicitly addresses aleatory variability: actual variation in loads experienced in scenarios of a given type.

Consistent with this general idea, in many design activities, “margin” is incorporated by specifying a through specification of a factor of safety (prescribed by engineering codes or good practices) to be applied to nominal loads in order to derive a specification of the “capacity” to be achieved in the design. For licensing nuclear plants in the US, a somewhat different approach was adopted in order to assure margin in emergency core cooling system (ECCS) performance. Under Appendix K [3], acceptance criteria are required to be met, conditional on selected severe challenges to ECCS function (e.g., large loss-of-coolant accident, concurrent with loss of offsite power, and the limiting additional single failure) and conditional on evaluation protocols that prescribe generally-conservative modeling choices (such as a factor of 1.2 applied to decay heat). This approach does not explicitly *model* the expected consequences of implementing a given ECCS design; it *bounds* specified consequences for a particular class of scenarios. This approach supports a surrogate-based decision rule, rather than an expected-utility decision rule. The limiting large LOCA concurrent with the most limiting offsite power situation and the most limiting single failure is meant to be a conservative proxy for anything that is likely ever to happen, at least for purposes of evaluating certain aspects of ECCS capability. Being a surrogate-based rule implemented with a conservative bias, it imposes significant costs on licensees, costs that have been discussed extensively elsewhere.

More recently, “Best Estimate Plus Uncertainty” approaches have been allowed [4]. Under these approaches, instead of dealing with epistemic uncertainty by making conservative modeling assumptions, one can make “best-estimate” choices, but also quantify uncertainty, and show that “there is a high probability that the [acceptance] criteria will not be exceeded” [4]. This process affords licensees some relief relative to the original ECCS rule. However, this evaluation process addresses what the Regulatory Guide [4] considers to be “calculational uncertainty,” not aleatory variation. That is, the evaluation is still carried out for the limiting break and the limiting single failure. As a result, the decision rule is now a better surrogate-

based rule, but it is still a surrogate-based rule. It allows best-estimate analysis of a conservatively chosen surrogate.

Within an expected-utility decision-making paradigm, surrogate-based rules are inherently suboptimal. If one can be sure that the surrogate-based decision rules are conservative in all ways, then the regulator's job is made easier by use of conservative surrogates. But the owner-operator is penalized by those rules. More broadly, expected-utility decision-making can be seriously distorted by the introduction of biases into the analysis, conservative or otherwise. For example, in deciding whether to replace a given SSC whose safety significance is minimal but whose operational significance is high, a "conservative" assessment of that SSC's remaining margin basically guarantees an expenditure to replace it, leaving highly uncertain the real need for that replacement.

2.2 Risk-Informed

The notion of "risk-informed" is associated with many ideas. The term appears to have originated in the early to middle 1990's at the Nuclear Regulatory Commission (NRC), in part to counteract naive advocacy of "risk-based" regulation that placed too much reliance on the outputs of quantitative risk models. The following recent concept of "risk-informed" appears on the NRC web site [5]:

Risk-informed regulation

An approach to regulation taken by the NRC, which incorporates an assessment of safety significance or relative [risk](#). This approach ensures that the regulatory burden imposed by an individual regulation or process is appropriate to its importance in protecting the health and safety of the public and the environment.

This notion of risk-informed is close to the intent of the Program Plan operating in this task. A risk-informed characterization of safety margin will focus on "loads" and "capacities" that actually matter within a risk-informed perspective, and characterize "risk-informed safety margin" in terms of those quantities.

Credit for Engineered Safety Features Within a Risk-Informed Perspective

In order to support decision-making based on safety measured in terms of actual risk to the public, it is necessary to go well beyond traditional accident analysis. This is true not only because traditional accident analysis is "conservative," but also because it was not originally formulated to quantify expected adverse consequences. Rather, it was formulated to try to assure that protection was "adequate."

As practiced in the nuclear industry, probabilistic risk analysis (PRA) tries to comprehensively quantify (or at least bound) the radiological risk to the public from reactor accidents. This entails going beyond traditional design basis accident analysis in the following ways:

- Taking credit in PRA for non-"safety" systems considering additional events; and
- Considering novel "safety" system applications, including systems operating in conditions where load may approach capacity.

This extension to the design-basis approach means that within a risk-informed perspective, the discussion of “margin” is more complicated than it is in design basis accident analysis. There are more success paths taking credit for “margins” of various types and degrees, and since these success paths are not “safety class,” the margins associated with them may be considerably reduced from the engineering-code-derived margins associated with safety-class success paths.

2.3 Risk-Informed Safety Margin

Design and licensing based on accident analysis of design-basis events laid much of the groundwork for the level of safety attained by the currently operating fleet. However, since the Reactor Safety Study, it has come to be appreciated that the safety perspective afforded by design-basis events and the single-failure criterion is not complete [6]. Investing in SSC performance based solely on the design-basis safety perspective is sub-optimal (in terms of actual safety compared to actual investment): it leads to over-investment in some areas, and under-investment in others. The latter point simply means that a safety case that is merely compliant with the design basis does not necessarily satisfy safety targets (such as the Quantitative Health Objectives) whose satisfaction is widely considered to be desirable (although the targets are not, of course, regulatory requirements).

Correspondingly, assessments of the public safety risk from the operating fleet are typically based on a broader set of success paths than the ones originally credited in the design basis safety case. These success paths may effectively be part of the licensing basis, to the degree that licensing basis decisions may be informed by risk analysis results, but this does not mean in every case that the margins associated with these success paths have received the same scrutiny as the margins emerging from the accident analysis success paths.

Table 1. Accident Analysis Margin versus “Risk-Informed Safety Margin”

	Safety Margin in Accident Analysis	Risk-Informed Safety Margin
Success Paths Being Analyzed for “Margin”	Conservatively formulated success paths in design-basis-accident analysis	Success paths making a significant contribution to a satisfactory risk result
Nature of Demonstration Regarding Margin	Pass / Fail: Analysis contains numerous deliberately conservative assumptions, so that showing $L < C$ for the path analyzed implies $L \ll C$ for realistic paths. Explicit quantification of $P(\text{Load} > \text{Capacity})$ not undertaken	Margins sufficient to ensure that $P(\text{Load} > \text{Capacity}) \ll P(\text{path hardware failure})$ and $P(\text{Load} > \text{Capacity}) \ll P(\text{Prevention Set Failure})$

Note: $P(x)$ means “the probability that condition x is satisfied”

The phrase “risk-informed safety margin” therefore refers to a view of margin based on this broader perspective. Accordingly, statements about margin now need to have meaning not only with respect to a design-basis event sequence, but more generally with reference to a non-design-basis sequence, or even group of sequences: a success path, or a family of success paths.

From a risk-informed perspective, we are interested in margins that govern the success probability of the paths that we are crediting, and we need to be sure that either they drive $P(\text{Load} > \text{Capacity})$ down to a level that is negligible in the context of the evaluation, OR that we can actually quantify $P(\text{Load} > \text{Capacity})$ and factor it into the evaluation. This implies a consistency criterion to be applied to success paths in a PRA, or collections of success paths (e.g., prevention sets):

$$P(L > C \mid \text{Hardware Success}) \ll P(\text{Hardware Failure})$$

Within a risk-informed perspective, increased attention is paid to actually quantifying this probability, or at least bounding it, and doing so for a range of success paths that are considered “beyond design basis.” The latter point arises because nowadays, the safety case actually used for many purposes is not the original design basis accident analysis, but rather a broader “risk” model.

Although traditional LWR safety analysis is a point of departure for one portion of the present development, it is necessary to go well beyond traditional safety analysis for present purposes. For decision-making purposes, instead of focusing on limiting instances of design-basis accidents, it is necessary to consider all probabilistically-significant scenarios, and all economically-significant end states.

3. NEXT-GENERATION ANALYSIS CAPABILITY

The last 10 years have seen significant work done on the idea of “margin” by many workers. Some of it [7-12] has taken place under the auspices of the Committee on the Safety of Nuclear Installations. This work is aimed primarily at regulatory interests; it is not focused on economic interests, and considers regulatory acceptance criteria rather than probabilistically treating capacity. Also, it seems to be based primarily on legacy safety analysis codes. However, it is similar to the present work in at least one key respect: “margin” is evaluated based in part on the probabilistic load spectrum. The CSNI work illustrates the essential value of this broader concept of margin. While concluding that the approach is feasible, the work also illustrates the computational effort associated with developing the probabilistic load spectrum, and, in more recent publications [10-12], stresses the application of intelligent supervision to the selection of code runs to increase the efficiency of the process.

For example, Zimmermann *et al.* [8] performed a “best-estimate plus uncertainty” (BEPU) analysis of the medium loss-of-coolant accident at a specific pressurized water reactor. They focused on a particular subset of scenarios (freezing out most aleatory degrees of freedom, a restriction that was relaxed in the more recent CSNI work), and analyzed uncertainty in peak cladding temperature (PCT) for a nominal-power case and an uprated-power case. They showed that the load distribution (probability density of peak cladding temperature) shifts very significantly between those two cases. The number of runs performed for each case was 93, based on “the Wilks formula for 2nd order statistics,” a thought process widely used to characterize the confidence level in the probability of exceedance of regulatory limits in LOCA analysis. For the scenarios analyzed, the exceedance probability was quite significant for the uprated case, and fairly significant even for the nominal case; this lack of margin is arguably not unexpected for scenarios that are beyond-design-basis, even though they were considered “success” for PRA purposes. Zimmermann *et al.* remarked the “challenges in properly sampling the tails [of the pdfs] to be further explored.” This work simultaneously

illustrates some of the challenges in analyzing margin, implicitly pointing out the practical effort of carrying out the task with current tools (TRACE, in their case), and the potential benefit of being able to do the analysis better.

However, other uncertainties also need to be addressed in order for the distributions in that example to be taken at face value in a decision process: the distributions need to reflect not only the uncertainties in the parameters that were varied in the 93 simulations, but also the uncertainties related to the code output for any given set of parameter inputs. These uncertainties relate to choice and implementation of models, numerical approaches, time stepping, and so on, and are not easily determined through a sampling process. Moreover, in order to be useful in a risk-informed decision process, the analysis needs to address a much broader class of aleatory issues than could be treated in that case study. Some of these were addressed in the more recent work [10-12].

In light of the above discussion, refer now to Figure 2, which suggests what “next-generation analysis capability” is meant to be, and what role it is intended to play. Focus initially on the green area labeled “Next-Generation Analysis Capability.” Within this area, two distinct activities are identified: (1) Generation, Characterization, Quantification of Scenarios, and (2) Analysis of Phenomenology of Probabilistically-Significant Events. Current-generation capability for analyzing phenomenology was developed originally to analyze specific scenarios (and this is essentially how it was used in the above-cited work by Zimmermann *et al.*). Current-generation risk analysis capability was developed with emphasis on the formulation of the scenario set, classification of families of scenarios into plant damage states, and the quantification of damage state frequencies, with some input from analysis of phenomenology. Beginning in the 1970’s with WASH-1400 [13], the two activities have been on different tracks, partly because of the very real difficulty of integrating them with the computational resources available.

Although it is important for these two activities to be coordinated, and recent years have seen increasing work to actually integrate them, complete integration of them remains a research activity. So-called “dynamic PRA” work integrating these two activities has been ongoing for some years. (For recent examples, see [14-22].) Much of this work has focused on driving the current phenomenology tools with probabilistically-informed scenario-generating algorithms. These approaches directly confront the problem of integrating the two activities. However, they are not easy to implement on a large scale because they demand a great deal of computing; and, more fundamentally, *the meaning of such calculations with current analysis tools would be in doubt even if they were performed, because unquantified uncertainties remain in the code outputs, even if the input parameter uncertainties are known and sampled.*

Correspondingly, as suggested in Figure 2, “Integrated Analysis of Probabilistically Significant Scenarios & Phenomenology” is a primary goal of the next-generation capability. This will be possible in the near term only through significant gains in the efficiency of analysis tools and an improved understanding of the state of knowledge actually implied by a given code output. Therefore, the present attempt is to re-engineer the phenomenology tool itself to have the following attributes:

- vastly improved numerics, providing much better convergence and the ability to move much more rapidly along the time axis,
- in-line modeling of all significant aleatory degrees of freedom (e.g., component failures), and coupling between those degrees of freedom and the phenomenology,

- in-line analysis of code uncertainty (parameter uncertainty and modeling uncertainty),
- the ability to solve efficiently for the limit surface,
- deployment of modeling and computational resources as necessary to reduce code uncertainty in a context-specific way.

Besides making a significant difference in the usefulness of the uncertainty analysis, these attributes will allow for much faster simulation of a given scenario at a given level of fidelity. This will make it much more to cover the probabilistically significant scenario set, running with higher fidelity where necessary, but running with reduced fidelity when the decision support needs do not warrant the higher fidelity.

Plant Decision-Making

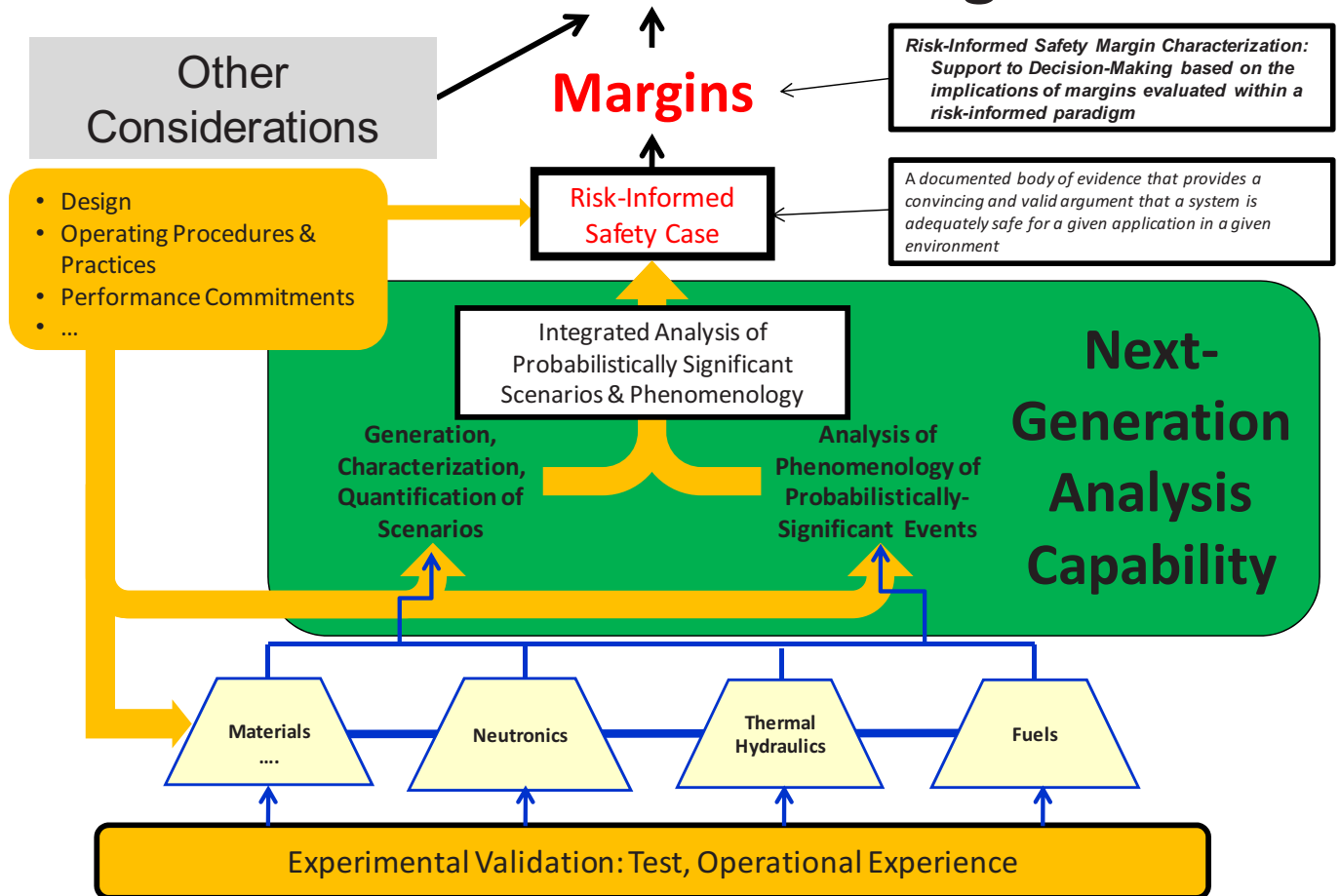


Figure 2. Analytical Support to Plant Decision-Making for Life Extension

4. SUMMARY

In order to support plant decision-making for life extension, analysis must address issues that go beyond traditional regulatory concerns:

1. plant economics depends on a broader range of SSCs and failure modes than are addressed by regulation, or by traditional safety analysis codes;
2. the decision processes need to be geared to realistically expected outcomes, rather than bounding evaluations.

The first point implies a broader scope of analysis. For example, consider events leading to overcooling of the reactor vessel to a degree that does not immediately threaten the public, but would compromise future plant operation. Such event states correspond to “success” outcomes in PRA space, but would cause significant adverse economic consequences. SSC degradation tending to increase the potential for such events is arguably of interest to plant decision-makers, and such events are arguably within the reach of current analysis capabilities, but are not typically addressed.

The second point implies a different *kind* of analysis: it requires not that uncertainty be bounded or eliminated, but that it be clearly understood. This understanding goes beyond what is required to show that an analysis is bounding. In fact, bounding analysis has significant shortcomings in many decision situations [23]. With regard to epistemic uncertainties, it is necessary to go beyond evaluation of model parameter uncertainties, to include the much broader topic of “code” uncertainty: to understand not only the variations in code output induced by variations in code inputs, but also to understand the uncertainty in code output due to the code’s models, meshing, time stepping, and numerics. With regard to aleatory uncertainties, the analysis needs to address the variations in equipment failure times, variations in initial conditions, etc. that generate the large variety of scenarios that determine real margin.

Earlier, it was noted that examples such as the CSNI work showed the feasibility of applying the approach, but on a relatively narrowly-scoped issue compared to the kinds of issues identified above. In order to make it practical to meet the above needs, existing safety analysis tools will arguably not suffice. It will be necessary to make a fresh start: different models, different solution techniques, and different outputs, to be applied within a different decision process. This work has begun, and progress so far is encouraging. It is hoped that a benchmark demonstration on a realistic LWR problem will soon be forthcoming.

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Nam Dinh	INL	Marty Sattison	INL
Karl Fleming	KNF	Curtis Smith	INL
John Gaertner	EPRI	Steve Unwin	PNNL
Dana Kelly	INL	Bob Youngblood	INL

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