Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division VII

OPPORTUNITIES FOR ADVANCING PERFORMANCE-BASED DESIGN METHODS FOR THE SEISMIC DESIGN AND REGULATION OF SSCS AT NUCLEAR POWER PLANTS

Robert J. Budnitz[1] and Michael W. Mieler[1,2]

[1] Earth Sciences Division, Lawrence Berkeley National Laboratory, Univ. of California, Berkeley CA (RJBudnitz@LBL.gov)
[2] Dept. of Civil and Environmental Engineering, Univ. of California at Berkeley, Berkeley CA

ABSTRACT

Dozens of seismic probabilistic risk assessments (SPRAs) exist that have analyzed large nuclear power plants (NPPs). A major insight from these SPRAs is that, although generally the plants are adequately safe against earthquake threats, the "seismic safety framework," meaning the way the industry and the U.S. Nuclear Regulatory Commission (NRC) now go about designing, building, operating, analyzing, and regulating seismic NPP safety, is far from optimal. This suboptimal framework means that for both operating NPPs and new NPP designs not yet built, the plants may cost more than they should, may fail to take advantage of possible additional safety insights and improvements, and are more difficult to analyze and to regulate than they should be. There is room for improvement in the framework in several areas, and most of the improvements are along the lines of making the framework more performance-based and/or risk-informed. The major topics covered herein are the variations in residual seismic risk from plant to plant; the unbalanced risk profiles and incomplete defense in depth achieved at many plants; the fact that structures and components are designed individually for seismic performance rather than taking a systems approach; the variations in "margin" that exist among the industry consensus codes and standards for seismic design and analysis; and the observation that the design codes and the NRC regulations do not "work together" well. Each of these topics is analyzed briefly here, and recommendations are presented that would improve the seismic framework in each of these areas

INTRODUCTION

Dozens of seismic probabilistic risk assessments (SPRAs) exist that have analyzed large operating LWR nuclear power plants (NPPs). A major insight from these SPRAs is that, although generally the plants are adequately safe against earthquake threats, the "*seismic safety framework*," meaning *the way the industry and the U.S. Nuclear Regulatory Commission (NRC) now go about designing, building, operating, analyzing, and regulating seismic NPP safety*, is far from optimal. This suboptimal framework means that for both operating NPPs and new NPP designs not yet built, the plants may cost more than they should, may fail to take advantage of possible additional safety insights and improvements, and are more difficult to analyze and to regulate than they should be. There is room for improvement in the framework in several areas, and most of the improvements are along the lines of making the framework more performance-based and/or risk-informed.

The major topics covered herein are:

- the variations in residual seismic risk from plant to plant;
- the unbalanced risk profiles and incomplete defense in depth achieved at many plants;

- the fact that structures and components are designed individually for seismic performance rather than taking a systems approach;
- the variations in "margin" that exist among the industry consensus codes and standards for seismic design and analysis; and
- the observation that the design codes and the NRC regulations do not "work together" well.

Each of these topics is analyzed briefly here, and recommendations are presented that would improve the seismic framework in each of these areas.

This is a summary --- a detailed paper is available that provides a more extensive description of the subject summarized here. See Budnitz and Mieler (2013).

ANALYSIS AND RECOMMENDATIONS FOR IMPROVEMENT, TOPIC BY TOPIC

For each of the 5 issues described above, there is now an opportunity for an improvement in the "seismic framework." For one of them, the issue of *unbalanced seismic risk profiles*, the opportunity can be taken advantage of in the very near term. Therefore, significantly more will be written below about this issue than about the others. However, each of the others is discussed, although progress on any of these issues will take longer, perhaps over the intermediate-term (a few years) or even only over a longer time period. This paper will attempt to explain why in each case.

Variations in Residual Seismic Risk

The risk profiles of the many NPPs analyzed with SPRA show a lot of variation from one plant to the next in terms of the overall seismic-induced core-damage frequency (seismic CDF). They also reveal a wide variation in the overall "seismic margin" of the plants above their individual seismic design bases. See NRC (2001). "Seismic margin" is defined herein as answering the question as to how much larger an earthquake than the one represented by the design basis can the plant withstand before it starts to get into trouble vis-à-vis accident sequences leading to core damage. While the term "seismic margin" is often used with a more specific definition, here we will use the term rather loosely in its common-language sense.

We are convinced that a lot of this variation in overall seismic margin can be reduced if the "seismic framework" is improved in the ways described in the rest of this paper.

Unbalanced Seismic Risk Profiles

This is the area where there is the largest opportunity for a short-term advance.

The risk profiles from the SPRAs show significant variation in how the various plants respond to earthquakes, particularly concerning which structures, systems, or components (SSCs) contribute most to seismic CDF. For many of the plants, the seismic risk profile is "unbalanced" in the sense that the seismic failure of a single SSC, or of a very small number of SSCs, contributes disproportionally and dominates the risk profile. Such an unbalanced risk profile means that the plant does not possess as much "defense in depth" as is typically desired. That is, a plant with strong defense-in-depth attributes would not possess a risk profile dominated by a single failure or a very small number of failures. Rather, the defense-in-depth philosophy strives to achieve a design in which the risk is more "balanced" among a variety of different contributors to overall risk.

There is a straightforward way to address this issue for a newly-designed plant. Specifically, our proposal is that, once a tentative design has been accomplished, an SPRA would be performed, and the risk insights from the PRA would be used to support certain iterations to improve the design. The improvements would have as their aim (i) to enhance the design's seismic "balance" vis-à-vis defense in depth; (ii) to enhance its seismic safety without adding important costs (and in fact perhaps with less cost); (iii) to provide a more transparent seismic safety case; or some combination of these.

The approach involves five steps:

(1) Complete a new NPP design using existing codes and standards, existing engineering practice, and existing regulations. This step follows existing practice. We have confidence that the methods to implement this Step exist and are widely used.

(2) Perform a PRA that includes a full SPRA, or that includes a Seismic Margin Assessment (SMA) using PRA-type systems-analysis methods. This Step also follows existing practice.

(3) Use the SPRA or SMA to identify the "leading" sequences and "leading" SSCs arising due to potential large earthquakes. A major objective of a design-stage SPRA or SMA is to develop an accurate understanding of the seismic "risk profile" of the new plant. In practice this comes down mainly to identifying those accident sequences that are the most important contributors to "seismic risk," often defined in terms of an annual core-damage frequency (CDF) and an annual large-early-release frequency (LERF). There are other figures of merit that may be used as well. One way or the other, the analyst, perhaps guided by the regulatory authority, will identify the "leading" seismic accident sequences in this Step. Within each seismic sequence, the PRA will identify the several SSCs that participate in that accident sequence. Please note that in some of these seismic sequences a human error will contribute or the sequence will include a so-called "non-seismic failure," namely a failure that occurs "randomly" (meaning not associated with the earthquake). See NRC (2001).

For each "leading" seismic sequence and its participating SSCs, the seismic "capacity," as measured by the probabilistic fragility curve, will be the way that the seismic failure is characterized, along with the specific failure mode, any common-cause failures that link this seismic failure in a correlated way with other failures, and any dependent or cascading failure issues, such as SSC #1's seismic failure causing the failure of SSC #2. Both the seismic capacity of the individual SSCs and the overall seismic capacity of the sequence are identified in this Step.

A further and important aspect of the PRA is that it can identify those few core-damage sequences that, because of various failures, lead to a so-called "large early release" rather than to a core-damage accident, which does not necessarily entail such a release. Avoiding such large early releases is a major objective of the design of any NPP, of course.

All of the above comprise elements of the "seismic risk profile" of the plant design, which is the end-point of the work in this Step.

(4) Compare the risk profile to a safety target, so as to provide the basis for a judgment as to whether the new design has an adequate measure of "safety." This involves more than one figure-of-merit to enable an evaluation of "how much" has been achieved in the way of "overall" safety. We note here that for new NPPs that require a design certification from the NRC, the NRC has a regulatory requirement that the plant-level HCLPF seismic capacity must exceed 1.67 times the design-basis earthquake level. See NRC (1993). This is a very useful "safety target" but not sufficient. Space does not permit our providing much more in the way of detail on this point. The interested reader is referred to the longer LBNL report that is the basis for this shorter SMiRT paper. See Budnitz and Mieler (2013).

(5) Evaluate the design for in imbalance in defense in depth.

<u>What is the issue or problem of defense-in-depth "balance" in our area, as we see it?</u> The issue is easy to explain, as follows. There are many SPRAs for NPPs in the literature. They contain a wide variety of conclusions and findings about the "seismic risk profile" of the specific plant being studied. As mentioned earlier, this "profile" consists of the set of the most important

seismic-initiated accident sequences, for each of which the PRA has identified the (usually small number of) seismic-induced failures, human errors, and non-seismic failures that participate in that sequence. The PRA also provides a numerical core-damage frequency (CDF) and/or a large-early-release frequency (LERF) for each such sequence. The summing of these represents the plant-wide CDF and LERF frequencies arising due to earthquakes.

The SPRA will have provided an analysis or description of the analyst's estimate of the uncertainty in the numerical values of CDF and/or LERF. The PRA will also have given insights into which of the various failures and errors are most important, and can provide comparisons between the seismic-initiated sequences and similar sequences initiated by other causes such as internal plant faults, other external events, or human errors.

Taken as a whole, the SPRA can also help a decision-maker address whether the plant is "safe enough," whatever that might mean to the individual decision-maker. Here it could mean "safe enough against earthquakes" or "safe enough" in a broader sense.

Back to defense in depth: One major insight from the numerous seismic PRAs in the literature for NPPs is that sometimes – in fact, often – the seismic "risk profile" is dominated by a single seismic failure in addition to the loss of offsite power. This failure can be, for example, the earthquake-induced damage to a major building (the auxiliary building or the turbine building), or the loss of all service water. In the jargon of PRA, this is a "singleton."

Let us suppose that the "leading" CDF seismic sequence is such a "singleton" sequence. Let us also suppose that, even so, the overall CDF (and LERF) is acceptably small, in a range that is within the "comfort zone" of safety decision-makers, whether in a regulatory agency or within the power plant's management. This fact, if true, would normally mean that the plant is "acceptably safe against earthquakes", whatever those words mean. However – and this is the point of this discussion – the whole rationale for a defense-in-depth approach to plant safety is that the overall acceptability of the plant's safety should not rest on a strength of a singleton, nor rely on a single line of defense, nor be dependent on the correctness of the analysis of a single item.

To put a fine point on it, *let us now assume that due to an error of some kind*, the "singleton" is actually *not as strong* against earthquakes as the PRA analysis says it is. There might have been an analysis error, the item as found in the field might be different from the item as analyzed from the drawings. Anchorage might be degraded, or fabrication errors might have occurred, or maintenance might have left the item in a degraded state, or the item might be vulnerable to failure due to the unrecognized potential for seismic damage caused by failure of another nearby structure or piece of equipment. Whatever the reason, the "singleton" is somehow not as "strong" as the PRA says it is.

This error, if true, would mean that the bottom-line findings of the entire seismic PRA are incorrect. However, neither the analyst nor the decision-maker knows it. *This type of situation is exactly why the overall philosophy of defense in depth has been developed and deployed – to avoid the situation where a single error related to a single item means that the NPP is more vulnerable than we think it is*.

Such a plant is "out of balance" vis-à-vis defense in depth. To restore an appropriate level of defense in depth, the plant design or layout or operations would need to be modified.

The policy question remains: What criterion should be used to determine "how much imbalance" is an undesirable amount of imbalance? Might it be some sort of percentage figure-of-merit, like "*defense-in-depth imbalance exists if a singleton sequence comprises more than 50% of the seismic risk profile"* or "*...more than 20%...*"? Might it be some sort of absolute CDF figure of merit like "*defense-in-depth imbalance exists if a singleton accident sequence has a mean sequence-specific CDF greater than* 1×10^{-5}*/yr* or 5×10^{-6}*/yr"?* Should the CDF and LERF endpoints be treated separately?

In today's NRC regulatory scheme, there are no criteria beyond a general qualitative exhortation to seek out and avoid imbalances when they are identified.

The solution, as a practical matter, is for the NRC to initiate a technical debate on this subject, ultimately leading to some sort of policy guidance -- perhaps a Commission policy position, perhaps a rulemaking, perhaps more general or less binding guidance. That this is needed is manifest if one accepts that many of the SPRAs in the literature contain "singleton"-type accident sequences as the leading (or nearly leading) contributors to the seismic risk profile. It goes without saying that this is also likely to be true of the many operating NPPs that have not yet been studied using SPRA methods.

In summary, a new policy proposal is advanced herein, that would bring to bear a more fully developed defense-in-depth philosophy to the design and analysis of the seismic performance of a new NPP. It would be aimed at reducing or eliminating a situation in which a new NPP's "seismic risk profile" is out-of-balance because the profile is unduly dominated by a seismic "singleton" – a single seismic-induced failure which makes an inordinately large contribution to the overall seismic risk arising from the plant. To achieve the goal outlined here would require new NRC policy development, in the form perhaps of a policy statement, a regulatory guide, or an actual regulation. How the form of this policy development would evolve is beyond the scope of the proposal described here.

SSCs are Designed Individually for Seismic Performance

Using today's approach, each SSC within an NPP is designed individually to achieve an adequate seismic capacity and performance. Both the design codes and the NRC's regulations take this approach for every SSC that is determined to be "safety related" and thus to need a specific design for earthquake loads. See NRC (1977); NRC (1996). [The term" safety-related" often has a specific regulatory definition, but here we will use the term in its more common-language sense to describe SSCs that contribute importantly to plant safety.] Insufficient account is taken of the role of a given safety-related SSC in contributing to the overall seismic safety of the plant. To say this in another way, the "systems view" of the plant does not generally play enough of a role in how individual SSCs are now designed and regulated against earthquakes.

To advance beyond this to account for the design and the safety of the "plant as a whole" will likely require a consensus code committee to address head-on how to use the systems insights from SPRA to modify the design guidance to account for the broader issues. The general process to be used here is similar to the multi-step process outlined above where we discuss how to go about addressing an unbalanced seismic risk profile. Specifically, one would complete the design using normal processes, then perform a full PRA that includes a seismic PRA, and then use insights from the risk profile of the plant-as-a-whole to account, where appropriate, for safety issues that the SPRA indicates are worthwhile considering. This might lead, for example, to the desire to strengthen the seismic design of one or more SSCs or alternatively to a possible lesser emphasis on certain other SSCs.

An approach like this could be part of the basis used by a consensus committee, charged with a seismic design code, to modify its approach to account for these types of plant-as-a-whole safety insights. To form the basis for the work of such a consensus committee, perhaps an individual researcher could take on the issue by writing a policy options paper that would become a focal point for discussion across the affected industry and the major professionals involved. The researcher could be a member of the NRC staff, or from an industry, academic, or consultant background. Perhaps an affected party could convene a "workshop" in which interested individuals can explore the issues thoroughly. Perhaps the NRC or EPRI could support a research project along these lines. It seems unlikely that progress can occur absent one or another of these precursor activities.

Variations in Margin Among the Industry Design Codes

The design of any individual SSC for service in a nuclear power plant is generally governed by one or another industry code or standard, usually endorsed by the NRC for its particular application. These consensus codes are developed and maintained by a number of code committees organized under different standards-development organizations (e.g., ASME, IEEE, ASCE, ACI, ANS, and others). These codes, which generally all rely on an externally specified "design-basis earthquake" as the starting point for the design, use a variety of different approaches for dealing with the issue of how much margin above the design basis is embedded in an SSC designed to "meet the code." That there are differences in embedded margin is not surprising, given that the committees have generally worked independently and that the consensus codes represent different philosophies of design related to the different fields of engineering. For example, it would only be through serendipity that the design of electrical components against earthquakes and the design of concrete shear walls against earthquakes would have taken similar approaches to embedded margin, given how different the design problems and design solutions are, and how differently the code committees in those areas went about developing the requirements.

None of the above is a criticism of the work of the various code committees. It is merely an observation about the differences in approaches and hence in the outcomes.

To advance beyond this, so as to achieve greater harmony across the various code committees leading to greater uniformity in the margins achieved, will likely require one of two catalysts: either an overarching body like the NRC could enforce some consistency of approach, or a consortium of the major code committees could somehow get together to bring this about. While the former would be "cleaner" and perhaps "easier" administratively, the latter might produce a result that ultimately has broader overall stature and staying power. To provide the intellectual framework, perhaps an individual researcher could take on the issue by writing a policy options paper, or perhaps a workshop could be assembled involving all of the major technical stakeholders, to try to work out (hammer out?) an agreed approach. Absent something like one of the above, most likely involving an entity with a stake in the outcome (for example, a regulatory agency like the NRC), it is not likely that a consistence in approach will be developed, meaning that the desired consistency of outcomes in terms of embedded seismic margin would not develop either. Currently, that consistency does not exist.

Coordination Between Design Codes and NRC Regulations

NRC's overall regulatory scheme for seismic safety involves much more than concerns with design: it involves concerns about construction, maintenance, operations, analyses (both analyses for regulatory compliance and realistic analyses to understand performance), and inspections. In an ideal NPP regulatory scheme, the design of individual safety-related SSCs against earthquake loads would "work together" with the NRC's safety regulatory scheme to achieve an overall NPP design with more than adequate safety margin. Also, judging the "adequacy" of that margin, which specifically falls within the purview of the NRC, would imply an NRC judgment accounting for both the desired margin and the desired confidence level.

Specifically, in an ideal Framework, the design of an individual safety-related SSC for earthquake safety according to a given code (say, a tank designed to an ASME code or an electrical component designed to an IEEE code) would use the design-basis earthquake (DBE) defined by the NRC as input. Each code embeds a certain amount of "margin" in the design, so that only an earthquake somewhat larger than the DBE can cause even the beginning signs of failure, and it would require an even larger earthquake to cause a high probability of failure to perform the required safety function. Certain construction, maintenance, inspection, and analysis requirements would also exist in a seamlessly laid-out scheme for achieving what is desired. The result would be an SSC whose seismic capacity would meet (or exceed) an NRC-established "target" needed for overall NPP safety.

This is what is meant by the phrase that an industry consensus design code and the NRC regulations would be "working together" to achieve a prescribed safety target.

The desired "working together" scheme is not in place today. This is because historically the NRC has neither had nor used safety "targets," nor was an attempt made by the NRC historically to bring about any measure of uniformity in the amount of margin between the seismic design basis and the seismic capacity achieved from one industry code to the next. It is of course quite unfair to state this in a way that implies that the engineering community (including the NRC) was somehow historically derelict in their duty – far from it. Everyone was doing the best they could, and all were acutely conscious of the limitations, including the variability of outcomes that would result. The fact is that when most of the operating US NPPs were designed, the philosophical underpinnings of the approach to "working together" did not exist, nor did the analysis tools exist that could be used routinely to ascertain whether the desired outcome (in terms of seismic capacity, described probabilistically by a fragility curve) would turn out as the NRC might desire or require.

However, today there has been an evolution on both of these fronts: (i) First, in the philosophy of NRC regulation, which is becoming more risk-informed and performance-based, and which is trying to integrate design, construction, maintenance, and inspection activities more fully; and (ii) second, in the ability of the code committees to embed a "working together" approach with the confidence that both analysis of the outcome of the design and a comparison against a target are feasible.

There are two broad institutional barriers to making sweeping progress on the agenda put forth in this report. One involves the NRC and the other involves the code committees.

<u>NRC Regulations</u>: How ripe is the NRC for a reassessment and revision to embed more risk-informed and performance-based requirements into the seismic regulatory Framework, along the lines discussed here? There has been major recent progress in the direction of overall new policy development at the NRC in this area. NRC's recent publication in April 2012 of NUREG-2150, *"A Proposed Risk Management Framework,"* not only lays out a roadmap for several significant new NRC policies, but it explains how they would fit together into a coherent agency-wide framework. See NRC (2012). This is, of course, only the beginning of a long process involving significant interactions with the regulated industry and the public. However, there is no doubt that over the long term this is the direction that a lot of new regulatory policy development will be following.

One issue of importance is whether the NRC's possible future approach will seek to differentiate between seismic design and analysis aimed at preventing core-damage accidents vs. aimed at preventing large early radioactive releases. This issue has not yet been "joined" through any extensive debate.

The authors are hopeful – guardedly hopeful – that substantial progress at the NRC will enable dialogue on the issues raised here.

<u>Code committees</u>: How ready are code committees for revisions along the lines of this report to their deterministic approaches to seismic design and analysis? Throughout the community of experts, the philosophy has been changing, slowly but inexorably, for years. Now this issue is ripe for even more movement toward performance-based design and analysis, if not risk-informed too, which is more difficult. It will take some leadership to follow up on the ideas embedded in NRC's NUREG-2150 report. See NRC (2012). One major piece of progress occurred when ASCE 43-05 paved the way. See ASCE (2005). A new version of ASCE 4 (that will supersede ASCE 4-98) is coming out soon and perhaps it will take the next steps. See ASCE

(2013). However, what is really needed is a common approach across the several different standards-development organizations that are active in this arena, including ASME, IEEE, ACI, ANS, and others. This will take industry-wide leadership that probably can only come from the NRC, although it is possible that it might emerge from a consensus of industry experts instead, or in addition. No forum now exists, however, that could sponsor or encourage the discussions that might lead to such a consensus of leading experts.

The goal ought to be not only that each major industry consensus design and analysis code embed the advanced philosophy discussed here, but also that there be coordination, so that the different technical areas "work together" to achieve comparable outcomes in terms of design and analysis of different categories of SSCs.

NRC and industry working together: How ready are these two major stakeholders to work together? We note that the industry consensus committees and the NRC do not yet "work together" to achieve a prescribed safety target, in major part because the NRC's current safety targets are not written in a form amenable for direct use by the code committees, and in part because working together has not historically been the pattern – the various code committees themselves have seldom seen either the need or the motivation to put in place uniformity in the safety achieved. And old habits die hard.

To advance beyond this will require an explicit decision, probably by the NRC staff with policy input from management (including the Commissioners), that achieving the desired uniformity is important enough to give priority to the effort required.

Fortunately, as noted above, "… today there has been an evolution on both of these fronts: (i) First, in the philosophy of NRC regulation, which is becoming more risk-informed and performance-based, and which is trying to integrate design, construction, maintenance, and inspection activities more fully; and (ii) second, in the ability of the code committees to embed a "working together" approach with the confidence that both analysis of the outcome of the design and a comparison against a target are feasible."

CONCLUSION

Several important opportunities exist, as outlined in this paper, for improving the "seismic framework," which is the way the industry and the U.S. Nuclear Regulatory Commission now go about designing, building, operating, analyzing, and regulation seismic NPP safety. As described herein, some short-term opportunities exist now, but some of the most important opportunities for advances will require policy shifts within both the industry and the NRC, along with a concerted effort to achieve more coordination than now exists.

REFERENCES

American Society of Civil Engineers. (2005). *Seismic Design Criteria for Structures, Systems and Components in Nuclear Facilities.* Standard ASCE/SEI 43-05. Reston VA

American Society of Civil Engineers (revision of ASCE 4-98. expected to be released in 2013). *Dynamic Analysis of Nuclear Structures.* Standard ASCE 4. Reston VA

Budnitz, R.J. and Mieler, M.W. (2013). "A Proposal for a More Risk-Informed and Performance-Based Framework for the Regulation of the Seismic Safety of Nuclear Power Plants". Lawrence Berkeley National Laboratory report. Berkeley CA

US Nuclear Regulatory Commission. (1977). "Seismic and Geological Siting Criteria for Nuclear Power Plants". Code of Federal Regulations, Title 10, Appendix A to Part 100. Washington DC

US Nuclear Regulatory Commission. (1993). "Policy, Technical, and Licensing Issues Pertaining to Evolutionary and Advanced Light Water Reactor (ALWR) Designs" SECY-93-087, April 2, 1993 and the Staff Requirements Memo SRM-93-087 that accompanied it on July 21, 1993. Washington DC

US Nuclear Regulatory Commission. (1996). "Earthquake Engineering Criteria for Nuclear Power Plants." Code of Federal Regulations, Title 10, Appendix S to Part 50. Washington DC

US Nuclear Regulatory Commission. (2001). "Perspectives Gained from the Individual Examination of External Events (IPEEE) Program." Report NUREG-1742. Washington DC

US Nuclear Regulatory Commission. (2012). "A Proposed Risk Management Regulatory Framework." Report NUREG-2150. Washington DC

ACKNOWLEDGMENT AND DISCLAIMER

The authors wish to acknowledge the strong intellectual support received from Dr. Annie Kammerer (US Nuclear Regulatory Commission's Office of Nuclear Regulatory Research), who also served as the technical contact on the NRC staff.

This manuscript has been written by authors at the Lawrence Berkeley National Laboratory under Contract No. DE-AC02-05CH11231 with the U.S. Department of Energy (DOE). The U.S. Government retains, and the publisher, by accepting the article for publication, acknowledges, that the U.S. Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for U.S. Government purposes. This project was supported by the U.S. Nuclear Regulatory Commission under a Federal Interagency Agreement with DOE.