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OPPORTUNITIES FOR IMPROVING THE REGULATIONS GOVERNING THE SEISMIC SAFETY OF LARGE NUCLEAR INSTALLATIONS

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ABSTRACT

Current seismic regulations for nuclear installations are generally adequate because when written, the regulators embedded large "conservatisms" to assure acceptable safety even in light of major technical uncertainties. However, at that time, nobody could perform realistic analysis of how these installations actually behave in large earthquakes. Hence, nobody could quantify the "margins," nor understand the major "risk contributors," nor know "how safe the plants are" against any useful figure of merit like the annual frequency of various radiation releases, nor know where there might be leverage for changes to improve safety. Unfortunately, the code committees that wrote (write) rules for the *parts* did (do) not interact; the consensus codes are based on different safety philosophies and very different (and generally unknown) margins of safety; and the development of seismic regulations is not coordinated, making them difficult to use together. This paper discusses opportunities to develop a common framework for seismic-safety regulation of nuclear installations (principally of nuclear power reactors), working with and through the code committees whose standards and codes govern nuclear seismic design and analysis. Disconnects between the codes and standards are identified. The paper discusses ideas that can be used to influence code-committee deliberations during the committees' periodic (5- to 10-year) re-evaluations. The ideas will enable the development of risk-informed codes and standards for the seismic design and analysis of the nuclear installations' structures, systems and components, including common risk targets to facilitate cost-effective designs that deliver specific levels of safety.

INTRODUCTION

Dozens of seismic probabilistic risk assessments (SPRAs) exist that have analyzed large operating 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 much 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. A recent report now in the publication process at the US NRC (Budnitz and Mieler, 2015), which parts of this paper are based upon, contains a discussion of a large number of these issues. Important issues in that report that are *not* covered in this paper include the issue of the variations in residual seismic risk from plant to plant, and the issue of the unbalanced risk profiles and incomplete defense-in-depth achieved at many plants. This paper will cover the following topics:

- the fact that structures, systems, and components (SSCs) 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.

These 3 topics are, of course, inter-related. Each of them is analyzed briefly here, and new initiatives are discussed that would improve the overall seismic framework.

ANALYSIS AND RECOMMENDATIONS FOR IMPROVEMENT

For each of the 3 inter-related issues described above, there is now an opportunity for an improvement in the "seismic framework." It is recognized that progress on this set of issues will take some time, requiring at least a few years but more likely requiring an even longer time period. The seismic framework described here is equally applicable, in principle, to other hazards for which nuclear power reactors must be designed and risk assessment performed.

SSCs are Designed Individually for Seismic Performance

Today, using the standard industry practice as endorsed by the NRC, each SSC within an NPP is designed individually to achieve an adequate seismic capacity and performance. Both the NRC's regulations and the design codes 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.] While some account is taken today of the role of a given safety-related SSC in contributing to the overall seismic safety of the plant, this plant-wide perspective is not a paramount consideration, and for some SSCs it is not important today at all. To say this in another way, the "systems view" of how the plant would respond in a large earthquake does not generally play a strong enough 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 in both the industry community and the NRC to change the current approach. Whether the NRC or the industry should take the initiative to start the process of changing things is not clear. However, it is clear that the process of change itself needs to begin with the code committees, with active NRC staff engagement.

The broad outline of the process that a consensus code committee (or, in reality, a group of such committees) would take to address head-on how to use the systems insights from SPRA to modify the design guidance is clear. The general process would be iterative. Specifically:

- one would first complete the design using the normal processes;
- next, one would perform a full PRA that includes a seismic PRA, including a realistic analysis of the seismic capacity (or fragility) of each important SSC;
- one would then use the 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;
- then one would revise the design, and develop a revised PRA to demonstrate overall adequacy.

This might lead, for example, to the desire (or the imperative!) to strengthen the seismic design of one or more SSCs, or alternatively to a possible lesser emphasis (reduced strength and less stringent detailing) on certain other SSCs because their contributions to the seismic risk are small.

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. The specifics, however, are intertwined with addressing the issue of margins embedded in the various codes, which is discussed next.

Variations in Margin Among the Industry Design Codes

As noted above, 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, AISC, ANS, and others). These codes, which generally all rely on an externally specified "design-basis earthquake" as the starting point for the seismic design, use a variety of different approaches for dealing with the issue of how much margin above the seismic 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, it is necessary to develop a vital piece of information to be used to inform the process. That information is a discussion, by each code committee for each design process, that *identifies the sources of the various margins* that are embedded in the design code, and the reason(s) for each embedded margin, and why the "size" or "amount" of the margin was selected. This may require an assessment of margins in archetype SSCs because codes and standards have been updated over decades of use with no explicit characterization of increase or decrease in safety. Without this information, it seems difficult to understand enough to provide the basis for different code committees to adjust their overall margins for greater consistency. This task, then, becomes one of the critical-path pieces of work to be accomplished before coordination across different areas can be approached, never mind accomplished. *It is, thus, one of the urgent tasks*, without which it is unlikely that a consistency 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.

The "feedback loop" from the analysis of the seismic safety of the actual plants to the code committees is vital. Code committees generally focus on component behavior (*e.g.*, forces in reinforced concrete shear walls) in earthquakes and do not generally consider the interaction of the components (*i.e.*, the system) in a seismic event. Specifically, using the seismic PRA process with its realistic analysis, the analysts need to identify where the margins really are for the various accident sequences of concern and the various safety functions and systems under consideration. Adjustments to the specific design then need to be made, but of greater significance is that feedback to the code committees needs to occur, resulting in a body of knowledge as to which aspects of which design codes produce what margins, and why. Importantly, PRA results and knowledge of component margins could inform the deterministic procedures adopted in codes and standards such as ACI 349 and AISC N690 (*e.g.*, by defining the return period of the design basis earthquake) to achieve specific system-level risk targets with the resultant design.

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: one that meets or exceeds the risk target. 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 pressurized 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. Of course, one needs a PRA (and specifically a seismic PRA) to understand whether a given design meets or exceeds the target, or perhaps falls short, and if so in which way(s).

The desired "working together" scheme is not in place today. This is because historically the NRC did not have or use 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. Indeed, *it is the existence of advanced realistic analysis tools that is the enabler of the rest of what is needed.*

Fortunately, today there has been an evolution in each of the major areas: (i) First, there have been major changes 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. (ii) Second, there is more *openness* on the part 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. (iii) Third, the existence of advanced, *realistic, probabilistic analysis of safety performance* is already enabling some progress, and as mentioned above is the key to enabling the more important future progress envisioned here.

What would "working together" mean in practice? First, the NRC would need to identify the targets for nuclear power plant seismic performance, presumably in a public process involving the public, the industry, and other stakeholders. This needs to start by safety targets at the plant-wide level (that is, plant-wide performance) but it must be more specific and more useful to designers than the broad plant-level "safety goals" (NRC, 1986) that are already part of the NRC safety philosophy, and the NRC's

HCLPF-based plant-level seismic criterion embedded in NRC's advanced-reactor policy (NRC, 1993). Whether this feeds down to targets for individual safety functions, or not, is a major item for discussion (the answer will probably be "yes"), but it almost surely should not feed down to targets for individual systems. Those system-level targets would need to be derived by each individual design team from the higher-level targets, so as to make the higher-level target(s) "come true." Then the designers would utilize the design codes developed by the various consensus code committees, achieving the appropriate targets for the plant-as-a-whole, or if necessary for the performance in earthquakes of the major individual safety functions. And in all of the above work, vital to achieving the rationality that such a new approach can offer would be cognizance of how much "margin" above the design basis is required (NRC's job!), and how much is achieved by the design codes working together (the code committees' job!), and *why*.

Barriers and Needed Actions

There are two broad institutional barriers to making sweeping progress on the agenda put forth in this paper. 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 publication in April 2012 of NUREG-2150, *"A Proposed Risk Management Regulatory 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 (NRC, 2012). NUREG-2150 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 much 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 radioactive releases. This issue has not yet been "joined" through any extensive debate.

<u>Code committees</u>: How ready are code committees to consider 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 risk-informed design, even if this will be slow. It will take some leadership to follow up on the ideas embedded in NUREG-2150. One major piece of progress occurred when ASCE 43-05 paved the way (ASCE 2005). A new version of ASCE 4 (to supersede ASCE 4-98) is due soon, and it will take small next steps; see ASCE (2015). However, what is really needed is a common approach across the several different standards-development organizations that are active in this area, including ASME, IEEE, ASCE, ACI, AISC, 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 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.

<u>NRC and industry working together</u>: How ready are these two major stakeholders to work together? We note that the 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 its 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 in each of the major areas: (i) First, there have been major changes in the philosophy of NRC regulation; … (ii) Second, there is more openness on the part of the code committees; (iii) Third, the existence of advanced, realistic, probabilistic analysis of safety performance … is the key to enabling the more important future progress envisioned here."

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.

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