INTRODUCTION

In this paper, the meaning of “risk-informed” is discussed in the context of power reactor design and operation and is related to the NRC guidance for an acceptable method to assess the nature and impact of changes using risk information [1]. As an application, risk-informed decision making is explained for the resolution of Generic Safety Issue 191 (GSI-191).

In summary, the guidance would have the NRC staff review changes by considering engineering issues and applying risk insights centered around five basic principles: (1) Changes should meet current regulations unless related to an exemption from, or a change to, a rule (10 CFR 50.12 or 10 CFR 2.802), (2) Changes are consistent with the defense-in-depth philosophy, (3) Changes maintain sufficient safety margins, (4) If a change results in an increase in core damage frequency or risk, the increase should be small and consistent with the intent of the Commission’s Safety Goal Policy, and (5) Changes should be monitored using performance measurement strategies. In addition, the methods, data, and criteria for considering risk should be appropriate for the decision being made.

The NRC risk-informed guidance does not preclude other approaches for requesting changes. Instead, the guidance is intended to improve consistency in regulatory decisions where risk analyses are used in regulation. In general, the risk-informed method of analysis differs from the deterministic (or classical) approach in that risk and uncertainty are quantified. In the deterministic regulatory analysis, risk (probability of failure) is assumed to be negligible as long as standards for design are met. In other words, meeting design requirements is assumed to be conservative. In risk-informed regulatory analysis, the risk of the design is quantified in a realistic setting (i.e., all risk contributors are included with their associated uncertainties) and the quantified level of risk can be observed and measured (i.e., managed). The primary advantage of working in a risk-informed regulatory framework is that limited resources can be properly allocated to the most important and significant problems.

The quantitative thresholds established in [1] have been implemented in several risk-informed applications [2-4]. However, the evolution of risk-informed regulatory framework continues. Recently, NRC led a Risk Management Task Force (RMTF) to develop a strategic vision with options for adopting a more comprehensive, holistic, risk-informed, performance-based regulatory approach for nuclear technologies [5]. The RMTF asks for regulations based on the best information available from research and operational experience. Citing from the NRC Strategic Plan (NRC, 2012), the RMTF reiterates that the expanded use of risk-informed and performance-based insights and the use of state-of-the-art technologies are the means by which the agency enhances the effectiveness and realism of NRC action [6].

Recently, the authors have been part of a multi-disciplinary technical team commissioned by the South Texas Nuclear Operating Company (STP) and have collaborated in a risk-informed pilot project [7] intended to close a long-standing regulatory concern [8,9], Generic Safety Issue 191, or GSI-191, which has, since 2001, eluded resolution despite significant efforts by industry and the NRC. The STP technical team is made up of specialists from academia and industry and is supported by national laboratories. This risk-informed GSI-191 project (the pilot project) has been used throughout this article as an example of a possible approach to incrementally implement the RMTF’s recommendations.

Although the pilot project began before the work by RMTF, in our opinion, it shares much of RMTF’s strategic vision for a risk-informed regulatory framework. In particular, the pilot project expands the use of risk-informed and performance-based insights and applies state-of-the-art technologies such as computer-aided design, advanced thermal-hydraulic codes (integration of RELAP and MELCOR), experimental methods, and advanced uncertainty quantifications and propagation methods in engineering models that are linked to the STP probabilistic risk assessment (PRA).

The approach used in the pilot project differs from previous risk-based efforts [10, 11] by: (1) using a risk framework to evaluate many of the engineering models developed over the twenty-year history, (2) adopting a different licensing approach based on the guidance provided in Regulatory Guide 1.174 [1], and (3) the incorporation of the engineering models (recast in a risk framework) to supply the STP PRA with certain basic events related to the concerns raised in GSI-191. The authors believe the work described here represents an
incremental step in commercial reactor risk analysis that could help form the foundation for further development of reactor regulation settings.

In the following, the technical concept of the pilot project methodology is summarized. It explains how the method differs from a deterministic path as well as how deterministic methods and models are integrated. The importance of using a similar methodology for other risk-informed nuclear power projects is also highlighted.

RISK-INFORMED RESOLUTION OF GSI-191:
THE PILOT PROJECT

Title 10 “Energy” of the Code of Federal Regulations (CFR) applies to all domestic commercial nuclear power stations. One of the several legal requirements defined in 10 CFR §50.46, “Acceptance Criteria for Emergency Core Cooling System (ECCS) for light-water nuclear power reactors,” is that events leading to a loss of long-term core cooling must be mitigated with high probability. The main purpose of the ECCS is to mitigate hypothesized Loss of Coolant Accident (LOCA) events by supplying cooling water to the reactor. LOCA events can be triggered by a valve failure or a structural failure and the ECCS is designed to accommodate the “worst case” of these failures with high probability of success.

On July 28, 1992, an event occurred at the Barsebäck Unit 2 boiling water reactor in Sweden in which an ECCS filter screen (referred to as containment vessel spray system filter screens at Barsebäck) plugged up with insulation material during a regularly scheduled test [12]. In the test, previously dislodged mineral wool was transported to the ECCS sump screen when the system test actuated the pumping system and two of the three system strainers became partially blocked. Two related events on January 16 and April 14, 1993, at the Perry Nuclear Power Plant, resulted from fibrous debris (in one event) and latent debris (in the other event) in the suppression pool. The second Perry event involved the deposition of filter fibers on these strainers. In the Perry event involving fibrous debris, the fiber collected corrosion products much more efficiently than the bare metal screen, resulting in a large pressure drop. Other events occurred after Barseback and Perry. After resolution of the BWR strainer issue through wide-scale strainer replacement, several years of phenomenology testing by the NRC regarding PWR ECCS screen performance prompted official declaration of Generic Safety Issue, GSI-191.

GSI-191 has eluded resolution despite significant efforts by industry and the NRC. Although recent thought had been given to risk quantification [10], and early recognition of the need for risk evaluation was identified, serious investigation into risk quantification had not been undertaken. Instead, resolution followed a classical deterministic approach. After an initial quantification [13], it became clear that, in conjunction with the design and operational changes made in response to the concerns raised in GSI-191, a risk-informed resolution path should be pursued for the STP project.

The method of analysis in the pilot project uses an integrative framework to explicitly provide failure probabilities for the post-LOCA PRA basic events associated with the concerns raised in GSI-191. Figure 1 depicts the two components of this integrated framework at a high level of abstraction. The first component (module 1 in Figure 1), illustrates the plant-specific LOCA branches of the PRA that includes risk scenarios and their associated fault trees. The second component (module 2 in Figure 1) contains models of the underlying physical phenomena associated with the basic events in module 1. In other words, module 2 (CASA Grande) provides estimated probabilities and the associated uncertainties to the basic events of the LOCA-PRA in module 1, based on the time-dependent physical models that have been developed for these basic events.

The goal of the CASA Grande (module 2 in Figure 1) is to propagate uncertainty in physical parameters from break initiation to potential core damage precursors: (a) strainer head loss, (b) core blockage, (c) boron precipitation, and (d) air ingestion. In other words, CASA Grande folds phenomenological uncertainties into plant performance metrics to support risk-informed decision making creating a platform for parametric studies, sensitivity analysis, and comparison of physical approximations. Uncertainty propagation is accomplished by assuming that the input parameters are random variables with distributions derived from historical data, experimental data, expert elicitation, physics, or a combination of these sources. Random observations from multivariate distributions that govern these parameters are generated using well-recognized sampling schemes. Finally, these values are propagated through CASA Grande to yield as output, an estimator of a key performance measure, such as the probability of a subsystem failure, which is then passed to the PRA model. We refer the readers to [14] for more details regarding CASA Grande uncertainty propagation technique.

The scope of the phenomena modeled in the pilot project is extensive, and includes location-specific LOCA frequency estimation, jet formation physics, debris generation, debris transport, effects of chemicals on head loss in debris beds, strainer head loss, degasification, downstream effects (i.e. in-vessel effects), and reactor thermal-hydraulics.

The advantages of the risk-informed framework can benefit and significantly improve the analysis required to address GSI-191 issues in multiple ways. First, it enables us to analyze the full spectrum of postulated LOCA events. Second, it ensures that physical processes are characterized as comprehensively and as realistically as
possible. Additionally, the probabilities and frequencies are quantified appropriately. Moreover, uncertainties are quantified based on observed uncertainties in experimental and operational data to include the possibility of extreme events. Uncertainties are not typically addressed in traditional deterministic analysis.

The purpose of the PRA quantification in this study (module 1 in Figure 1) is to quantify the risk and uncertainty in the as-built, as-operated plant associated with the safety concerns identified in GSI-191. The PRA quantification forms the basis for “mitigative measures and an alternative method approach” that the NRC staff identified as a GSI-191 closure path in 2012 (Nuclear Regulatory Commission, 2012 [15]). The results of the pilot project showed that the risk of core damage or large early release related to the concerns raised in GSI-191 in the as-built, as-operated design for STPNOC is very small (as defined in Regulatory Guide 1.174 [1]). We refer the readers to [7] for more details regarding the technical aspects of the pilot project.

SUMMARY AND CONCLUSION

Generally, a risk-informed analysis will involve a relatively broad spectrum of disciplines and realistic engineering analysis as required in NRC guidance. Traditionally, engineering analysis in commercial nuclear power applications has lacked detailed uncertainty analysis and quantification. Instead, “worst case” or credible extremes are evaluated separately. Where uncertainty has been evaluated [16, 17], it is not clearly related to risk or scenario importance. Quantification of risk and uncertainty is a basic need in a risk-informed regulatory paradigm.

The risk-informed pilot project developed and used a new integrative approach, which could be more suitable in the risk-informed regulatory setting. More specifically, in this project (a) underlying physical and chemical models for the post-LOCA PRA basic events, associated with the concerns raised in GSI-191, were developed outside the PRA and (b) uncertainties were propagated in the physical models in order to have their results ready to
be incorporated into PRA. The probabilities of the basic events (and their associated uncertainties), as they were obtained from the models of the underlying physical and chemical phenomena, were then incorporated into PRA. The uncertainties in the probabilities of basic events were also propagated through the PRA scenarios.

The risk-informed pilot project is unique in some aspects such as it: (1) advances the PRA methodologies and applications by the integration of underlying physical and chemical phenomena, (2) presents the state-of-the-art integration of probabilistic methods (e.g., uncertainty analysis, statistical analysis, risk analysis) and deterministic techniques (e.g., experimental testing, computer-aided design, and computational fluid dynamics), and (3) arose from collaborative work by teams of experts from industry and academia. The risk-informed project started in academia, but without private sector industry support, practical implementation would not have been possible. The utility and, particularly, its sector industry support, practical implementation have also significantly benefitted from the discussions and feedback received from regulatory experience. The progress of the research and its implementation have also significantly benefitted from the discussions and feedback received from regulatory representatives.

The methodology used in the pilot project can be applied for other risk-informed projects related to nuclear power plants. Some of the authors are currently proposing to apply a similar methodology to fire PRA [18] and seismic PRA [19]. Another important area is the incorporation of underlying safety culture and organizational factors into risk-informed regulation. One of the authors has worked in this area of research [20] and, is advancing the benefits for applications to the nuclear power industry.

REFERENCES