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Original Article

A Review of the Progress with Statistical Models of Passive Component Reliability

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ABSTRACT

During the past 25 years, in the context of probabilistic safety assessment, efforts have been directed towards establishment of comprehensive pipe failure event databases as a foundation for exploratory research to better understand how to effectively organize a piping reliability analysis task. The focused pipe failure database development efforts have progressed well with the development of piping reliability analysis frameworks that utilize the full body of service experience data, fracture mechanics analysis insights, expert elicitation results that are rolled into an integrated and risk-informed approach to the estimation of piping reliability parameters with full recognition of the embedded uncertainties. The discussion in this paper builds on a major collection of operating experience data (more than 11,000 pipe failure records) and the associated lessons learned from data analysis and data applications spanning three decades. The piping reliability analysis lessons learned have been obtained from the derivation of pipe leak and rupture frequencies for corrosion resistant piping in a raw water environment, loss-of-coolant-accident frequencies given degradation mitigation, high-energy pipe break analysis, moderate-energy pipe break analysis, and numerous plant-specific applications of a statistical piping reliability model framework. Conclusions are presented regarding the feasibility of determining and incorporating aging effects into probabilistic safety assessment models.

1. Introduction

Nuclear power plant piping systems are robustly designed and carefully fabricated. However, even a well-designed piping system can develop through-wall leaks or ruptures. Piping reliability analysis has been a topic of discussion and concern within the nuclear safety community for a long time [1]. In part, this concern has been related to the capabilities and limitations of available methods and techniques, as well as with the requirements for how to best perform "pedigreed" quantitative analysis in support of probabilistic safety assessment (PSA) applications. The introduction of risk-informed in-service inspection (RI-ISI) [2], risk-informed resolution of GSI-191 [3], and the evolving internal flooding PSA

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methodology [4] are but three examples of how nuclear industry initiatives have contributed to the current set of pipe failure databases and associated analysis tools and techniques. Analytical insights from a broad spectrum of piping reliability analysis case studies performed over a 2-decade period have been translated into a guideline for how to structure a robust piping reliability analysis task in support of practical, PSA-oriented applications.

The team of analysts responsible for the seminal Reactor Safety Study (WASH-1400) [5] performed a limited evaluation of nuclear power plant piping reliability based on service experience from the then approximately 150 U.S. commercial nuclear reactor operating years [6]. This evaluation was aimed at estimating loss-of-coolant-accident (LOCA) frequencies for input to the two PSA models (Peach Bottom Unit 2 PSA and Surry Unit 1 PSA) that constituted the Reactor Safety Study. After the publication of WASH-1400 in 1975, many other research and development projects have explored the roles of structural reliability models and statistical evaluation models in providing acceptable input to PSA. Furthermore, during the past 20 years' efforts have been directed towards the establishment of comprehensive pipe failure event databases as a foundation for exploratory research to better understand the capabilities of today's piping reliability analysis frameworks.

Against a historical overview of past efforts, this paper addresses the question how to best utilize service experience data for quantitative piping reliability analysis. Significant progress has been made to develop pipe failure databases, as well as analysis tools to explore and analyze the body of service experience with piping from today's well over 15,000 commercial reactor operating years and 11,000+ records on pipe degradation and failure events. Insights from 25 years of pipe failure database applications and method development are utilized to reach some conclusions about the capability of statistical analysis approaches to piping reliability analysis. Also addressed are guidelines and good practices for how to optimize the utilization of service experience data when structuring piping reliability analysis strategies.

The ability of an event database to support practical applications is closely linked to its completeness and comprehensiveness. Equally important is the knowledge and experience of an analysts in interpreting and applying a database given typical project constraints. Achievement of database "completeness" and "comprehensiveness" is motivated by an in-depth understanding of the application requirements. These requirements are linked to three general types of applications: (1) high-level; (2) risk-informed; and (3) advanced database applications. Here the term "risk-informed" implies an application that is performed using the best available and most current information concerning piping degradation mechanisms and their mitigation, and in a context of the current probabilistic safety assessment practice.

Data specialization is an intrinsic aspect of all PSA oriented applications. This encompasses several specific analysis tasks such as the review and assessment of the applicability of industry-wide service experience data to a plant-specific piping design (e.g., material, dimension, piping layout, and operating environment), development of *a priori* failure rate distribution parameters reflective of unique sets of piping reliability attributes and influence factors, and Bayesian update of apriori distributions. The update may encompass consideration of different "what-if" scenarios such effect of different degradation mechanism (DM) mitigation strategies or impact of a corrosion resistant material as opposed to carbon steel.

2. Historical review

The WASH-1400 study included an evaluation of piping reliability to derive "order-of-magnitude" LOCA frequencies and pipe failure rates. Different, nuclear, and non-nuclear sources of service experience data and pipe failure rate data were utilized for the purpose of extrapolating pipe failure rates for input to the PSA models of the WASH-1400 study.

With funding from the US Nuclear Regulatory Commission Office of Research, the Idaho National Laboratory has performed studies to update the LOCA frequencies of WASH-1400. The report NUREG/CR-4407 [7] accounted for the accumulated US service experience through December 1984, and NUREG/CR-5750 [8] expanded the evaluation to account for service experience through end of 1997. The nuclear industry through the Electric Power Research Institute (EPRI) has also sponsored research and development to develop databases and associated methods and techniques for piping reliability analysis [9–11]. During 2003–2006, the Nuclear Regulatory Commission established an "Expert Panel on Loss-of-coolant Accident Frequencies" [12] to develop LOCA frequencies for boiling water reactor (BWR) and pressurized water reactor plants. An expert elicitation process was utilized to consolidate service experience data and insights from probabilistic fracture mechanics (PFM) with knowledge of plant design, operation, and material performance. LOCA frequencies were developed for three distinct time periods: (1) present-day estimates; (2) end-of-plant life (i.e., at time $T = 40$ years); and (3) at $T = 60$ years estimates to reflect state at the end of a first license renewal cycle.

In the late 1980s, the American Society of Mechanical Engineers (ASME) recognized the need for risk-informed methods in the formulation of codes and standards, and guides by organizing a research task force on RI-ISI. From this work, ASME was able to demonstrate that risk-informed methods offered the potential to technically enhance the existing ISI programs. The current RI-ISI methodology includes extensive considerations of piping reliability. The methodology, process, and rationale used to determine the likelihood of pipe failure is required to be scrutable and available for independent review. The RI-ISI initiatives refocused the investigations into the application of service experience data to derive insights about pipe failure potential and pipe failure probability. An intrinsic technical aspect of these RI-ISI initiatives is the role of new piping service experience and its potential influence on an existing RI-ISI program plan.

In a series of reports by the Swedish Radiation Safety Authority [13–15], the evolution of statistical models of piping reliability is summarized; from the mid-1960s to the mid-

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