Letter Report

Technical Review of STP LOCA Frequency Estimation Methodology

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1. INTRODUCTION

This letter report summarizes the results of an independent limited scope technical review of the Development of LOCA Initiating Event Frequencies for South Texas Project (STP) [1] Two rounds of review were preformed, first on an earlier draft (dates August, 2011), and later on the draft final report (dated September 2011). Throughout the process clarifications were sought from the authors of the report, and suggestions were made on the technical approach, results, and report content. Key recommendations made in this process were addressed by the authors and are reflected in the final report [1].

The scope of the review was limited to (a) LOCA Frequency Estimation Model, (b) interpretation and use of NUREG-1829 [2] information, and (c) other key assumptions and computational steps utilized to generate the numerical results. In the following sections we first provide an overview of the basic elements of report's methodology for estimating STP LOCA frequencies and offer general comments on the methodology and its basic assumptions. Next we provide specific comments on the steps of the methodology and their implementation. Finally we provide an overall assessment and key conclusions of this review.

2. LOCA FREQUENCY ESTIMATION MODEL OVERVIEW

The scope of the current STP LOCA study is to estimate the frequency of LOCAs initiated at or near the location of pipe and nozzle welds. The report indicates that future work would include LOCAs due to pipe failures at other locations and non-pipe related failures in the RCS pressure boundary.

2.1 Basic Estimation Model

The report's model for estimating the frequency of a LOCA of a given size is given by the following equations:

$$F(LOCA_x) = \sum_i m_i \rho_{ix} \tag{1}$$

where,

$$\rho_{ix} = \sum_k \lambda_{ik} P(R_x | F_{ik}) I_{ik} \tag{2}$$

(x refers to the various break size ranges such as those used in NUREG-1829 to describe the 6 LOCA categories). The terms in equations 1 and 2 are defined in the following table [1].

$F(LOCA_x) =$	Frequency of LOCA of size x, per reactor calendar-year, subject to epistemic uncertainty calculated via Monte Carlo
$m_i =$	Number of pipe welds of type i; each type determined by pipe size, weld type, applicable damage mechanisms, and inspection status (leak test and NDE); no significant uncertainty
$\rho_{ix} =$	Frequency of rupture of component type i with break size x, subject to epistemic uncertainty calculated via Monte Carlo or lognormal formulas
$\lambda_{ik} =$	Failure rate per weld-year for pipe component type i due to failure mechanism k, subject to epistemic uncertainty determined by RI-ISI Bayes method and Eq. (2.3) below
$P(R_x \vert F_{ik}) =$	Conditional probability of rupture of size x given failure of pipe component type i due to damage mechanism k, subject to epistemic uncertainty determined via expert elicitation using NUREG-1829 data
$I_{ik} =$	Integrity management factor for weld type i and failure mechanism k, subject to epistemic uncertainty determined by Monte Carlo and Markov model

A point estimate for the failure rate per weld due to a mechanism k is given by

$$\lambda_{ik} = \frac{n_{ik}}{\tau_{ik}} = \frac{n_{ik}}{f_{ik} N_i T_i} \tag{3}$$

where

$n_{ik} =$	Number of failures in pipe component (i.e., weld) type i due to failure mechanism k; very little epistemic uncertainty
$\tau_{ik} =$	Component exposure population for welds of type i susceptible to failure mechanism k, subject to epistemic uncertainty determined by expert opinion
$f_{ik} =$	Estimate of the fraction of the component exposure population for weld type i that is susceptible to failure mechanism k, subject to epistemic uncertainty, estimated from results of RI-ISI for population of plants and expert opinion
$N_i =$	Estimate of the average number of pipe welds of type i per reactor in the applicable reactor years exposure for the data collection, subject to epistemic uncertainty, estimated from results of RI-ISI for population of plants and expert opinion
$T_i =$	Total number of reactor-years exposure for the data collection for component type i; little or no uncertainty

Different locations are characterized and assigned rupture frequencies based on 45 combinations of system type, weld type, degradation mechanisms, and pipe size. The estimation process is a “bottom-up” approach building the LOCA estimates by combining various contributing components, failure mechanisms, and conditional probabilities.

2.2 Comments and Observations

The general decomposition formula (Equation 2) used by the report to estimate LOCA frequencies follows known principles of the calculus of probability. The formula represents the widely used constant failure rate model, but similar to the approach taken by NUREG-1829, an approximate way of allowing aging effects is introduced by applying factors to increase failure rates from one period in plant life to another.

A key advantage of this formulation is that it enables the consideration of known susceptibilities to the damage mechanisms in quantification of the failure rates and conditional probabilities. It allows tailoring the probabilities for component-specific vulnerabilities to various degradation mechanisms.

As a physical model, the decomposition formula views pipe rupture (LOCA) as a two-stage process involving (1) stochastic occurrence of degraded functional conditions, and (2) stochastic rupture events given a degraded condition. The formulation offers a reasonable first order approximation of a physical process model. Similar formulations are seen elsewhere in PRAs for instance in Accident Sequence Precursor (ASP) methodology and some of the popular methods for common cause failure analysis such as the *Beta Factor* and *Binomial Failure Rate* methods.

A key advantage of the approach is the ability to make use of existing operational data in various forms, including information on observed degraded states and early stages of pipe and weld failure, as indicators of far less frequent rupture events. In addition, the parameter I_{ik}, (in Equation 2) determined through a previously developed and peer-reviewed Markov model [3], provides the ability to account for the effects of integrity management programs on reducing likelihood of catastrophic failures.

The report makes a number of other modeling assumptions and simplifications during implementation. For instance, various degradations (crack, small leak, leak, etc.) are lumped together as a homogenous class, irrespective of their implied severity (here the "probabilistic distance" to rupture events). This means that the same conditional rupture probability applies to all degraded states. The effect is overestimation for some (e.g., crack) and underestimation for other degraded conditions (e.g., leak), with the expectation that the net effect on rupture rates is negligible and residuals are well-covered by large ranges of uncertainty applied throughout.

Elsewhere the report linearly combines the contributions of various damage mechanisms at a specific piping location, to determine the total LOCA frequency distribution (for each weld /location). This is a first order approximation to a significantly more complex case where synergetic effects of multiple damage mechanisms are considered explicitly. However, the state of the art in experimental results and theoretical physics of failure models for the synergistic effects of failure mechanisms is quite limited. It can be argued that to a certain extent the net effect of synergistic phenomena are accounted for through the use of actual data in the failure frequency estimation stage. That is, the actual failure events used by the report to estimate failure frequencies include events where one or several physically possible failure mechanisms were at work, even when only a single failure mechanism is declared as the culprit.

3. FAILURE RATE DEVELOPMENT STEPS

The report provides a list of key steps of the methodology for estimation of the failure rates. Using the same list, we summarize our observations and comments on the methods applied:

1.1 Determination of component and weld types

- Outside the scope of this review

1.2 Perform data query for failure counts

- Outside the scope of this review

1.3 Estimate component exposure

- Outside the scope of this review

1.4 Develop component failure rate prior distributions for each damage mechanism (DM)

- This aspect of the methodology is based on earlier well-established work in EPRI RI-ISI [3], which has been peer reviewed by industry, academia, and NRC. Therefore no detailed review of this part of the methodology was performed in effort. We have noted the report's appropriate use of very wide lognormal distributions, based on existing pipe failure rates, engineering judgment, and use of data.

1.5 Perform Bayes' update for each exposure case (combination of weld count case and DM susceptibility case)

- This part of the methodology is a standard use of Bayesian updating (mostly with 0 failures) which is well established and accepted in PRAs. Computations were done with aid of a validated and widely RDAT computer code.

1.6 Develop mixture distribution to combine results for different exposure hypotheses to yield conditional failure rate distributions given STP specific applicable DMs

- Use of (equally weighted) mixture of distributions to generate a composite distribution for different data assumptions is an accepted (advanced) methodology within the Bayesian framework. The report has applied this methodology in a very systematic and rigorous way.
- Mixture distributions are developed using standard Monte Carlo sampling technique and numerical procedures. However, the specifics of the numerical implementation were not subject of this review.
- While the process and assumptions are clearly stated (see for example Table 3-1 of the report [1]) the scope of this review did not include an evaluation of the technical basis for assumptions made in the process of estimating population size for each class (weld, pipe segment, etc.) and in engineering

assessing the level of susceptibility of each class to various failure mechanisms

1.7 Calculate total failure rate over all applicable damage mechanisms

- To generate the distribution of total failure rates standard Monte Carlo sampling technique and numerical procedures are used. The numerical implementation however was not a subject of this review.

4. CONDITIONAL RUPTURE PROBABILITY ESTIMATION

The goal of this part of the methodology is to develop a set of conditional rupture probabilities (CRPs) vs. break size for each component category. CRPs are estimated by anchoring the generic total frequency of each of the six LOCA classes on two distinct sources of NUREG-1829 data [2]: (a) Base case analyses of specific PWR components (hot leg, surge line, HPI line for a specific 3-loop PWR) developed by B. Lydell using methodology similar to that used by the current study, and (b) Estimates of 9 experts of LOCA frequencies vs. break size for many PWR components for the entire fleet of U.S. PWRs.

The report provides a list of key steps of the methodology for estimation of the CPRs. Using the same list, we summarize our observations and comments on the methods applied:

2.1 Select components to define conditional rupture probability (CRP) model categories

- Outside the scope of this review

2.2 Obtain expert reference LOCA distributions from NUREG-1829

- (see comments under 2.3)

2.3 Obtain expert multiplier distributions for 40yr LOCA frequencies from NUREG-1829

- Some NUREG-1829 experts had provided asymmetric inputs for lower, middle, and upper values, which were inconsistent with lognormal distribution characteristics. NUREG-1829's approach to deal with such cases was to use "split lognormal distributions" (a synthesis of two half lognormals). The STP approach fits the asymmetric cases to standard lognormal distribution in part to simplify the procedure. Of the three possible alternatives, this reviewer recommended use of Upper and Mid values to determine fit a lognormal distribution. The advantage of this choice is that it preserves the central tendency of the distribution (often the starting point by experts) and keeps the expert's upper bound estimate, which carries more risk significance.

2.4 Determine 40yr LOCA distributions (product of steps 2.2 and 2.3) for each expert, fit to lognormal

- This is done for each expert's estimate prior to aggregation of the result of 9 experts (correct approach among alternatives). The procedure follows basis probability rules for developing distribution of product of lognormally distributed quantities.

2.5 Determine geometric mean of expert distributions from Step 2.4 (lognormal)

- The report investigated two approaches for forming composite distributions (a) Mixture Distribution Method (with equal weight for all experts), and (b) Geometric Mean Method (by taking the geometric means of two parameters of the experts' lognormal distributions, medians and range factors). The Geometric Mean method, which is the approach taken by NUREG-1829 was also adopted by the report. In this reviewer's opinion, in general the mixture distribution approach to expert opinion aggregation has a stronger technical basis. However, an equally important factor is the engineering assessment by NUREG-1829 and the STP report of the overall suitability of the results produce by each approach.

2.6a Benchmark Lydell Base Case Analysis for selected components

2.6b Determine failure rate distribution for Lydell Base Case analysis in NUREG-1829; fit to lognormal

2.6c Apply Lydell CRP model from Base Case Analysis

2.6d Determine LOCA frequency distribution from Lydell Base Case Analysis

- Steps 2.6(a)-(d) replicate the steps of previously applied methods, which also provided a reference estimate in NUREG-1829. The steps also parallel many of the steps of ref [1]. As such further review was regarded as unnecessary.

2.7 Determine mixture distribution of NUREG-1829 GM (from Step 2.5) and Lydell LOCA frequency (from Step 2.8) to obtain Target LOCA frequency Distribution for each CRP category component

- The report has viewed NUREG-1829 expert opinions and Lydell's approach as two largely separate sources of information on LOCA frequencies. This reviewer agrees that the overlap of the two sources are less pronounced than the differences in corresponding modeling and quantification approaches. Of possible options for use of these two sources of information, and based on a recommendation form this reviewer, the report has chosen a mixture of distributions based on (1) aggregation of NUREG-1829 expert estimates using geometric mean method, and (2) Lydell's results.

2.8 Apply formulas to calculate CRP distributions to be used as prior distributions for each component assigned to each CRP category

- This step is straightforward conceptually, but requires relatively complex set of steps in carrying the needed Monte Carlo numerical procedures. This review however did not look into the details of computational implementation.

2.9 For each component in CRP category, perform Bayes update with evidence of failure and rupture counts from service data

- This step follows standard approach to Bayesian updating (beta prior distribution and binomial likelihood). Updating is done with marginal distributions (beta) of each of the six CRP categories given a failure. The joint distribution of CRPs is a multinomial distribution but separate updating with marginal (beta) distribution for each CRP is a reasonable simplification with no visible impact on results give the low values of CRPs.

5. SUMMARY AND CONCLUSIONS

This report has summarized the results of an independent review of the report on Development of LOCA Initiating Event Frequencies for South Texas Project [1]. The scope of the review was limited to (1) LOCA Frequency Estimation Model, (2) interpretation and use of NUREG-1829 information, and (3) other key assumptions and computational steps used to generate the numerical results. The review process identified a number of improvements on the technical approach and implementation process that were addressed prior issuing the final report by the authors. Examples include (1) addition of a more detailed summary of the methodology and charts explaining its steps, (2), better explanation of assumptions, both in constructing the model and in its numerical implementation, and (3) more consistent application of probabilistic methods in some areas (e.g., approach to synthesis of different sources of information).

Overall the modeling and parameter estimation approaches of the report were found to be sound, acknowledging a number of common approximations and simplifying assumptions, some imposed by the limitations in the state of the art. The report has applied a systematic approach for identifying various sources of uncertainty and quantifying their effects. These include allowing for expert-to-expert and model-to-model variability, and accounting for known sources of aleatory and epistemic uncertainties. The systematic treatment of uncertainties well as the report's use of relatively broad ranges for distributions of various model parameters, are expected to cover much of the impact of modeling and implementation assumptions, including those that stem from limitations in the state of the art. Further sensitivity analyses can highlight any potential need to fine-tune the impact of assumptions and approximations.

6. REFERENCES

1. Development of LOCA Initiating Event Frequencies for South Texas Project GSI-191, Final Report for 2011 Work Scope, Revision 1, Developed for South Texas Project Electric Generating Station, by Karl N. Fleming (KNF Consulting Services LLC) and Bengt O. Y. Lydell and Danielle Chrun, Scandpower Risk Management Inc., Oct 2011.
2. Tregoning, R., L. Abramson, and P. Scott, "Estimating Loss-of-Coolant Accident (LOCA) Frequencies through the Elicitation Process", NUREG-1829, U.S. Nuclear Regulatory Commission, Washington, DC, April 2008.

3. Fleming, K. N. and B. O. Y. Lydell, "Database Development and Uncertainty Treatment for Estimating Pipe Failure Rates and Rupture Frequencies," Reliability Engineering and System Safety, 86: 227–246, 2004.