Technical Review of STP LOCA Frequency Estimation Methodology

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Scope of Review

- LOCA Frequency Estimation Model
- Interpretation and use of NUREG-1829 information
- Other key assumptions and computational steps used to generate the numerical results
- Two rounds of review were done, one on an earlier draft (Early August, 2011), and one on the final report (dated Sept 2011)

LOCA Frequency Estimation Model Overview

- Current report has focused on estimation of the frequency of LOCAs initiated at or near the location of pipe and nozzle welds
- Future work will include LOCAs due to pipe failures at other locations and non-pipe related failures in the RCS pressure boundary

Basic Estimation Model Overview

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

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

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

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

- x refers to the various break size ranges such as those used in NUREG-1829 to describe the 6 LOCA categories.

Definitions

$F(LOCA_x) =$	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
$P(R_x \mid F_{ik}) =$	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

Definitions

$n_{ik} =$	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

Basic Estimation Model Overview

- 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.

Basic Estimation Model
Comments and Observations

- The general decomposition formula follows known principles of calculus of probability
- The formula represents the commonly made assumption of constant failure rate model for the selected period in plant life
- The formulation enables the consideration of known susceptibilities to the damage mechanisms in quantification of the failure rates and probabilities
- It allows tailoring the probabilities for component-specific vulnerabilities to degradation mechanisms

Basic Estimation Model

Comments and Observations

- Parameter I_{ik}, determined through a previously developed and peer-reviewed Markov model, provides the ability to account for the effects of integrity management programs on reducing likelihood of catastrophic failures
- As a physical model the decomposition formula views the pipe rupture (LOCA) process as a two stage process of (1) stochastic occurrence of degraded functional conditions, and (2) stochastic rupture events given a degraded condition
- This is a reasonable first order approximation of a physical process model. Similar formulations are seen elsewhere in PRA such as Precursor Event methodology and some of the commonly used methods for common cause failure analysis analysis

Basic Estimation Model Comments and Observations

- A key advantage of the approach is the ability to make use of existing operational data
- Assumptions in implementation
  - Various degradations (crack, small leak, leak etc) are lumped together as one homogenous class irrespective of their implied severity
  - This means that the same conditional rupture probability applies to all degraded states. The effects is overestimation for some (e.g., crack) and underestimation for other degraded conditions (e.g., leak)

Basic Estimation Model Comments and Observations

- The contributions of various DMs at a specific piping location are combined linearly 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 DMs are considered explicitly. However, the state of the art in terms of experimental results and theoretical models for the synergistic effects is quite limited
- To some extent the the net effect of synergistic phenomena are accounted for via the use of actual data in the failure frequency estimation estimation stage

Failure Rate Development Steps

- 1.1 Determination of component and weld types
- 1.2 Perform data query for failure counts
- 1.3 Estimate component exposure
- 1.4* **Develop component failure rate prior distributions for each damage mechanism (DM)**
- 1.5* **Perform Bayes' update for each exposure case (combination of weld count case and DM susceptibility case**)
- 1.6* **Develop mixture distribution to combine results for different exposure hypotheses to yield conditional failure rate distributions given STP specific applicable DMs**
- 1.7 Calculate total failure rate over all applicable damage mechanisms

* Subject of specific comments on next viewgraph

Observations on Failure Rate Development Steps

- **STEP 1.4 Develop component failure rate prior distributions for each damage mechanism (DM)**
  - From earlier work in EPRI RI-ISI, peer reviewed
  - Very wide lognormal distributions, based on existing pipe failure rates, engineering judgment, and use of data
- **STEP 1.5 Perform Bayes' update for each exposure case (combination of weld count case and DM susceptibility case**)
  - Standard use of Bayesian updating (mostly with 0 failures), well established and accepted in PRAs
  - Computations were done with aid of a validated and widely used computer code

Observations on Failure Rate Development Steps

- **STEP 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
  - The applied Monte Carlo sampling technique and numerical procedures were not subjects of this review
  - While the process and assumptions are clearly stated (see for example table 3-1) 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, ect,) and in assessing the level of susceptibility of each class to various failure mechanisms

Conditional Rupture Probability Estimation Methodology

- The goal is to develop a set of conditional rupture probabilities (CRPs) vs. break size for each component category
- CRPs are estimated by anchoring the the generic total frequency of each of the six LOCA classes on two distinct sources of NUREG-1829 data
  - 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
  - Estimates of 9 experts of LOCA frequencies vs. break size for many PWR components for the entire fleet of U.S. PWRs

Conditional Rupture Mode Probability Model Steps

- 2.1 Select components to define conditional rupture probability (CRP) model categories
- ***2.2 Obtain expert reference LOCA distributions from NUREG-1829**
- ***2.3 Obtain expert multiplier distributions for 40yr LOCA frequencies from NUREG-1829**
- ***2.4 Determine 40yr LOCA distributions (product of steps 2.2 and 2.3) for each expert, fit to lognormal**
- ***2.5 Determine geometric mean of expert distributions from Step 2.4 (lognormal)**

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Observation on CRP Estimation Steps

- **STEPS 2.2 and 2.3**
  - Some NUREG-1829 experts had provided asymmetric inputs for lower, middle, and upper values, inconsistent with lognormal distribution characteristics
  - NUREG-1829 used “split lognormal distributions” to treat this asymmetry. 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 the corresponding distribution
    - preserves the central tendency of the distribution and
    - keeps the expert’s upper bound estimate which carries more risk significance

Observation on CRP Estimation Steps

- **STEP 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

Observation on CRP Estimation Steps

- **STEP 2.5 Determine geometric mean of expert distributions from Step 2.4**
  - The report investigated two approaches for forming composite distributions,
    - Mixture Distribution Method (with equal weight for all experts)
    - 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.

Conditional Rupture Mode Probability Model Steps

- 2.6a Benchmark Lydell Base Case Analysis for selected components
- 2.6 b 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
- ***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**
- ***2.8 Apply formulas to calculate CRP distributions to be used as prior distributions for each component assigned to each CRP category**
- ***2.9 For each component in CRP category, perform Bayes update with evidence of failure and rupture counts from service data.**

* Subject of specific comments on next viewgraph

Observation on CRP Estimation Steps

- **STEP 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, the report has chosen a mixture distribution of GM and Lydell results, following a recommendation form this reviewer.

Observation on CRP Estimation Steps

- **STEP 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 careful numerical (MC) procedures. This review however did not look into the details of computational implementation

- **STEP 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 and binomial likelihood)
  - Updating is done with marginal distributions (beta) of each of the 6 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

Summary and Conclusions

- Comments and suggestion on earlier version have been addressed in the final report. Examples include
  - Addition of a more detailed summary of the methodology and charts explaining the steps
  - Better explanation of assumptions
  - More consistent application of probabilistic methods in some areas

Summary and Conclusions

- The modeling and parameter estimation approaches are found to be sound, acknowledging a number of common approximations and certain simplifying assumptions, some imposed by the limitations in the state of the art
- The report's careful and comprehensive treatment of known sources of uncertainty as well as relatively broad rages assigned to distributions are expected to cover much of the impact of the assumptions and limitations in the state of the art