Uncertainty modeling of LOCA frequencies and break size distributions for the STP GSI-191 resolution

Elmira Popova, David Morton
The University of Texas at Austin
May 2012

1 Introduction

In the initial quantification (Crenshaw, 2012), Fleming et al. (2011) performed a substantial study designed to build upon the established EPRI risk-informed in-service inspection program (EPRI, 1999). The methodology of EPRI (1999) was used as the primary basis to develop the size and location-specific rupture frequencies for the initial quantification. Although the overall methodology appears to be sound based on peer review (Mosleh, 2011) and reasonableness of the values obtained, NRC feedback in the Pilot Project reviews has resulted in further review of the approach. In this paper we propose a new approach to assign location-specific LOCA frequencies derived from the overall frequencies, as defined in Tregoning et al. (2008), which we refer to as NUREG-1829.

The NUREG-1829 annual frequencies are neither plant specific nor plant-location specific. Yet they are used throughout the nuclear industry as an important input to PRA analyses, and therefore, they need to be preserved. Conservation of the NUREG-1829 break frequencies is our guiding principle.

In this document we work with the six categories defined in Table 1, NUREG-1829 Volume 1, page xxi, as "effective break size" for the PWR plants. Table 1 shows the mapping between the NUREG-1829 notation and ours. In addition, we use the term *distribution* to mean a distribution function—either cumulative distribution function (CDF), probability density function (PDF), or probability mass function (PMF)—of a random variable used to model a specified uncertainty.

Table 1: LOCA categories notation map

Effective break size (inch) for PWR	Notation
$\frac{1}{2}$	cat_1
$1\frac{5}{8}$	cat_2
3	cat_3
7	cat_4
14	cat_5
31	cat_6

We should point out that South Texas Project PRA analysis uses only three LOCA categories, small, medium, and large. Our proposed methodology can be applied to any finite number of break-size categories.

In this document we will use the term *location* to represent a specific *weld case*, using the terminology of Fleming et al. (2011). Overall there are two distinct approaches to derive location- or weld-case-specific LOCA frequencies: bottom-up and top-down. The first approach requires location specific failure data to estimate the corresponding probability of a weld failure. Suppose a break occurs and assume there are M_j different welds in the plant where breaks of size cat_j can occur, $weld_1, \ldots, weld_{M_j}$, then using the law of total probability we can write:

$$P[cat_j] = \sum_{i=1}^{M_j} P[cat_j|weld_i]P[weld_i],\ j = 1, 2, \ldots, 6,$$

where $P[cat_j]$ is the probability of a cat_j LOCA given that a break occurs, $P[cat_j|weld_i]$ is the conditional probability of a cat_j LOCA given that the break occurs at weld i, and $P[weld_i]$ is the probability that the break occurs at weld i, where again, weld i represents *weld case* i, using the terminology of Fleming et al. (2011).

In the bottom-up approach we first must determine $P[cat_j|weld_i]$ (using estimation or expert elicitation). Then, if we assume that each location is equally likely to have the break, we can multiply by $1/M_j$ and sum the resulting probabilities to obtain the total probability the break is a cat_j LOCA. If the bottom-up approach is followed the resulting total cat_j LOCA probability will *not* equal the number provided in NUREG-1829 (or at least it is very unlikely to yield that number). This approach, taken by Fleming et al. (2011), is an inherently bottom-up approach. In an attempt to preserve the NUREG-1829 frequencies Fleming et al. (2011) developed an approximation scheme. In their review, the NRC technical team raised several questions about using this as a “stand alone” methodology, which has led us to take a different path.

The approach that we propose to take is rooted in the combining the top-down and bottom-up approaches: We start with the NUREG-1829 frequencies and develop a way to distribute them across different locations proportionally to the frequencies estimated using the bottom-up approach. In this way, we maintain the NUREG-1829 frequencies overall but also allow for location-dependent differences. We should point out that we use the location specific tables as defined in Fleming et al. (2011). To our knowledge no other sources of location specific frequencies exist. If such information becomes available our proposed methodology can immediately incorporate that information.

For a top-down approach, we will use again the cat_j LOCA as an illustrative example. The LOCA frequencies (NUREG-1829 Volume 1, page xxi, Table 1) are cumulative and so we compute the probability of a LOCA being in cat_j using the formula

$$P[cat_j] = \frac{Frequency[LOCA \geq cat_j] - Frequency[LOCA \geq cat_{j+1}]}{Frequency[LOCA \geq cat_1]},$$

for $j = 1, \ldots, 6$ and where $Frequency[LOCA \geq cat_7] \equiv 0$. Again we assume there are M_j different locations in the plant where breaks of size cat_j can occur, $weld_1, \ldots, weld_{M_j}$. Assume, for the moment, given that we have a cat_j break, these M_j locations are equally likely to have the break, i.e.,

$$P[weld_i | cat_j] = \frac{1}{M_j}, \; i = 1, \ldots, M_j.$$

Then we have $P[cat_j \text{ at } weld_i] = P[cat_j]P[weld_i|cat_j]$ and so $P[cat_j \text{ at } weld_i] = P[cat_j]/M_j$. Finally, applying the law of total probability,

$$P[cat_j] = \sum_{i=1}^{M_j} P[cat_j \text{ at } weld_i],$$

we see that the resulting probability of a cat_j LOCA matches exactly the NUREG-1829 probability. The approach we propose in this document, follows the steps we have just outlined, except we propose replacing the simple assumption of a cat_j break being equally likely to occur across all locations with an approach that uses location-specific conditional probabilities that we infer from Fleming et al. (2011).

The above methodology distributes equally the LOCA frequencies as defined in NUREG-1829 Table 1 across all locations that can experience breaks from one or more of the six size categories. The six break size categories (from the NUREG-1829 Table 1) represent six bounded intervals. For a particular weld we need to be able to sample from the continuous interval of break size values. In addition, we would like to be able to sample from the distribution of the frequencies. The rows in Table 1 from NUREG-1829 represent the distribution of the frequencies by reporting the mean, median, 5th and 95th percentiles. We will use this information to fit six continuous distributions for each break size category.

2 Proposed Methodology

2.1 Fitting distribution to the LOCA frequencies

We first describe how we fit a distribution to the frequencies for each break size category. In theory, there are an infinite number of distributions that one can fit to the LOCA frequencies represented in NUREG-1829. For example, two split lognormal distributions are used in NUREG-1829 and gamma distributions are used in NUREG/CR 6928.

We choose to fit the bounded Johnson distribution, (Johnson, 1949) for the following reasons:

- The Johnson has four parameters, which will allow us to match closely the distributional characteristics provided by NUREG-1829. In order to obtain the parameters of the Johnson distribution we solve an optimization problem with constraints defined by the distributional characteristics.

- The Johnson distribution allows for a variety of shapes. In particular, skewed, symmetric, bimodal, or unimodal shapes can be obtained.

The cumulative distribution function (CDF) of the bounded Johnson is:

$$F[x] = \Phi\left\{\gamma + \delta f[(x-\xi)/\lambda]\right\},$$

where $\Phi[x]$ is the CDF of a standard Normal (0,1) random variable, γ and δ are shape parameters, ξ is a location parameter, λ is a scale parameter, and $f(z) = \log[z/(1-z)]$. We restricted our attention to bell-shaped PDF curves only. This was achieved by imposing a constraint $\gamma \geq 1$ in our fitting algorithm. The fitted parameters of the Johnson distribution for each of the six categories are given in Table 2. The comparison between the NUREG-1829 distributional characteristics of the LOCA frequencies and the fitted ones are presented in Table 3. We note that the expert elicitation was for the 5%, 50% (median), and 95% quantiles, and did not involve eliciting the mean parameters. So we focus on matching the parameters elicited from the experts as indicated by the results in the final four columns of Table 3. The six panels in Figures 1 and 2 show the fitted PDFs of the Johnson distribution for each category. Once the best fit is found, we sample the LOCA frequencies for each category to obtain $Frequency[LOCA \geq cat_j]$—a realization of the cumulative LOCA frequency to be in category j or larger.

2.2 Distribution of LOCA frequencies to different weld locations

We first convert the sampled LOCA frequencies to probabilities using

$$P[cat_j] = \frac{Frequency[LOCA \geq cat_j] - Frequency[LOCA \geq cat_{j+1}]}{Frequency[LOCA \geq cat_1]}, \quad (1)$$

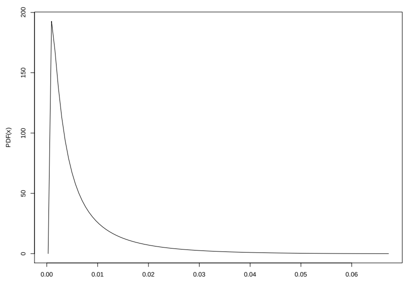
where

Table 2: Fitted Johnson parameters

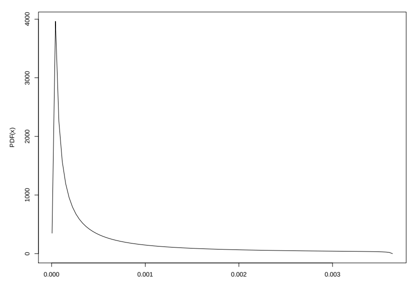
	Johnson Parameters			
	γ	δ	ξ	λ
Cat1	2.144623E+00	7.507774E-01	2.597254E-04	6.698783E-02
Cat2	1.365229E+00	4.195681E-01	4.822843E-06	3.646760E-03
Cat3	1.392766E+00	4.196874E-01	1.415507E-07	9.377713E-05
Cat4	1.701576E+00	4.554581E-01	5.609081E-09	1.302968E-05
Cat5	1.906196E+00	3.825140E-01	2.573251E-10	1.730668E-06
Cat6	2.525065E+00	3.816999E-01	1.853162E-11	8.868925E-07

Table 3: NUREG-1829 and fitted Johnson median, low and high quantiles values

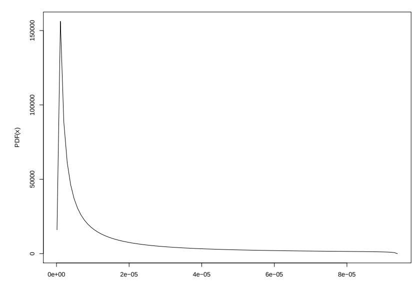
	NUREG 1829 Values				**Fitted Johnson**				**Relative Error**			
	5th	**Median**	**Mean**	**95th**	**5th**	**Median**	**Mean**	**95th**	**5th**	**Median**	**Mean**	**95th**
Cat1	6.90E-04	3.90E-03	7.30E-03	2.30E-02	6.89E-04	3.90E-03	6.68E-03	2.30E-02	**0.20%**	**0.00%**	8.56%	**0.00%**
Cat2	7.60E-06	1.40E-04	6.40E-04	2.40E-03	7.61E-06	1.39E-04	4.97E-04	2.41E-03	**0.14%**	**0.38%**	22.37%	**0.62%**
Cat3	2.10E-07	3.40E-06	1.60E-05	6.10E-05	2.09E-07	3.42E-06	1.24E-05	6.07E-05	**0.52%**	**0.53%**	22.69%	**0.49%**
Cat4	1.40E-08	3.10E-07	1.60E-06	6.10E-06	1.40E-08	3.09E-07	1.20E-06	6.12E-06	**0.01%**	**0.28%**	24.97%	**0.25%**
Cat5	4.10E-10	1.20E-08	2.00E-07	5.80E-07	4.18E-10	1.20E-08	9.91E-08	5.81E-07	**1.99%**	**0.28%**	50.47%	**0.17%**
Cat6	3.50E-11	1.20E-09	2.90E-08	8.10E-08	3.45E-11	1.21E-09	1.65E-08	8.04E-08	**1.42%**	**0.43%**	43.27%	**0.75%**



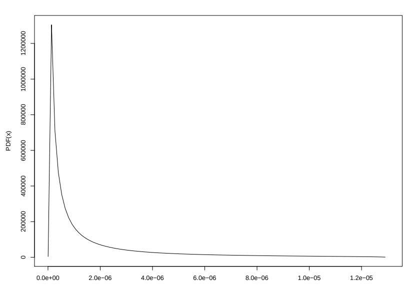
(a) Cat1



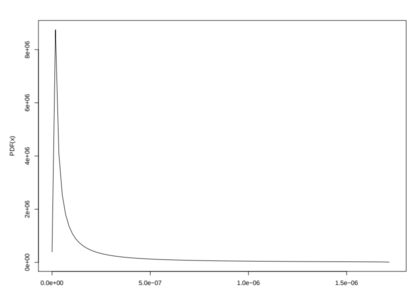
(b) Cat2



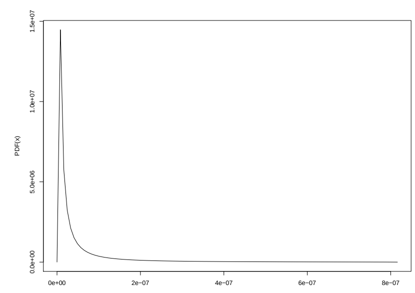
(c) Cat3



(d) Cat4

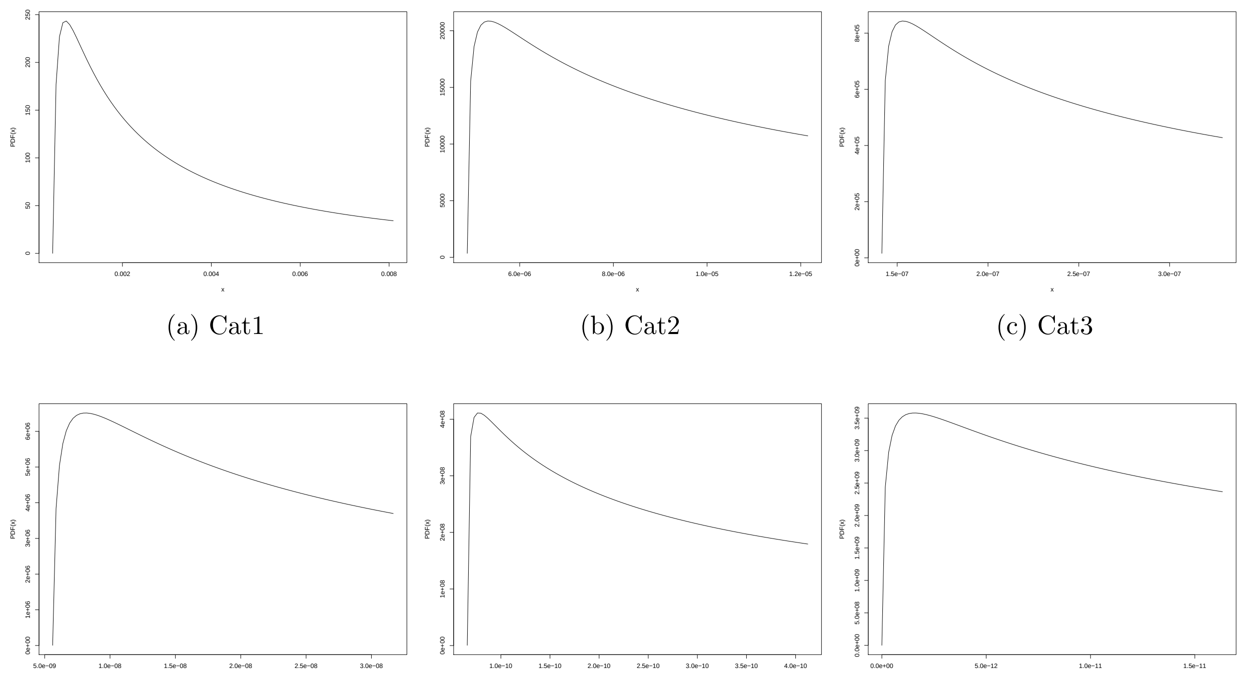


(e) Cat5



(f) Cat6

Figure 1: Johnson PDF for each category



(a) Cat1 (b) Cat2 (c) Cat3

(d) Cat4 (e) Cat5 (f) Cat6

Figure 2: Johnson PDF for each category, zoomed to a narrower range of frequencies near the modes of the distributions

- $J = \{cat_1, cat_2, cat_3, ..., cat_B\}$: set of possible break types (categories),
- $P[cat_j]$: probability of observing a break that falls into category j given that a break was observed
- $Frequency[LOCA \geq cat_j]$: frequency of break of type j or larger, $j \in J$
- $Frequency[LOCA \geq cat_{B+1}] \equiv 0$.

As we describe above, there are a total of $B = 6$ categories in NUREG-1829. Given $P[cat_j]$, the next step is to distribute that probability across all welds that can experience a break from that particular category. Not all types of welds can experience all types of breaks. We use I_j to denote the subset of locations that can have a break from category j.

We compute the probability that weld i will experience a break of type j using $P[cat_j \text{ at } weld_i] = w_j^i P[cat_j]$, where $w_j^i = P(weld_i|cat_j)$ is the conditional probability of the break occurring at weld i given that we have a category j break. Restated, w_j^i is the fraction that weld i contributes to category j's total break frequency from the bottom-up approach for $i \in I_j$. Computation of w_j^i is straightforward. The bottom-up approach generates the frequency of category j breaks at location i, which we denote $Freq_{bu}[LOCA \geq cat_j \text{ at } weld_i]$. Given these frequencies, the w_j^i values can be computed using:

$$w_j^i = \frac{Freq_{bu}[LOCA \geq cat_j \text{ at } weld_i] - Freq_{bu}[LOCA \geq cat_{j+1} \text{ at } weld_i]}{Freq_{bu}[LOCA \geq cat_1 \text{ at } weld_i]}. \quad (2)$$

Given $P[cat_j]$ from equation (1) and w_j^i from equation (2), we form

$$P[cat_j \text{ at } weld_i] = w_j^i P[cat_j]. \quad (3)$$

Since the sum of all w_j^i across $i \in I_j$ is equal to one, with this approach we are guaranteed to match the NUREG-1829 specified values for $P[cat_j]$.

2.3 Sampling of the break size

The final step is to sample the actual break size conditioned on the break category. Here we assume that the break size has a uniform distribution within a given category. Formally, we write

$$breakSize_j^i \sim U[minBreak_j^i, maxBreak_j^i],\ j \in J, i \in I_j,$$

where

- $minBreak_j^i = cat_j^{minBreak}$
- $maxBreak_j^i = \min\{cat_j^{maxBreak}, weld_i^{size}\}$
- $cat_j^{minBreak}$ – minimum break size that would put it into category j
- $cat_j^{maxBreak}$ – maximum break size that would put it into category j
- $weld_i^{size}$ – actual weld size (it cannot experience break size larger than its diameter).

2.4 Methodology summary

Our approach requires two sampling loops in our simulator CASA GRANDE, Letellier (2011). We need one sampling loop for the break size within each category and an outer loop that samples LOCA frequencies. Below is a step-by-step description of the procedure:

1. Input: N, the number of LOCA frequency samples, and S, the number of break size samples to generate.

2. Sample LOCA frequencies $Frequency[LOCA \geq cat_j]$, $j = 1, 2, \ldots, 6$, from the fitted Johnson distributions for each break category; see Section 2.1.

3. Distribute uncertainty across plant-specific welds as described in Section 2.2.

4. Sample break size for each possible weld / break-category combination as described in Section 2.3.

5. Estimate, and store, performance measures using CASA GRANDE.

6. Go to step 4 and repeat until we obtain S break-size samples.

7. Compute, and store, performance measures.

8. Go to step 2 and repeat until we have obtained N LOCA frequency samples.

9. Form the summary of aggregated performance measures.

3 Illustrative Example

We illustrate the approach we describe in the first four steps from Section 2.4 using the following example. Assume we have a total of six welds and these are the only locations where a break can occur. Three of them (welds 1, 2 and 3) are small and have sizes of 1.7, 2, and 2.5 inches and hence can experience only small breaks (category 1 and category 2). Two of those six (welds 4 and 5) are of medium size and have a diameter of 3.8 inches and thus can have small and medium breaks (category 1, category 2, and category 3 only; they cannot experience category 4, or larger, breaks). The last weld (weld 6) is large with a size of 35 inches and can have all types of breaks—small, medium, and large (category 1, . . . , category 6). A graphical representation of the system is shown in Figure 3.

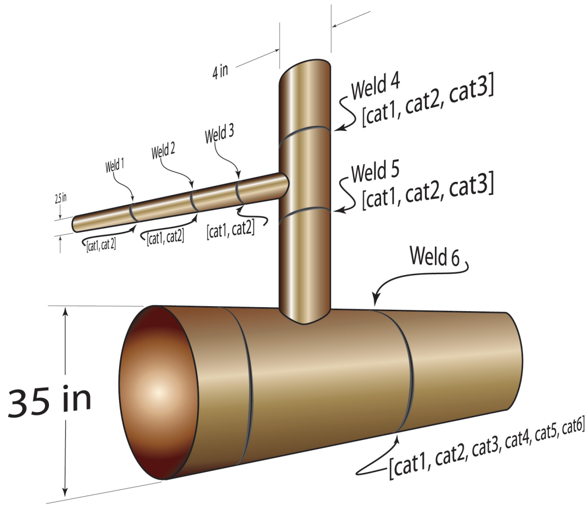


Figure 3: Example system depiction with six welds of various sizes that can each experience some subset of six types of breaks from category 1,. . . ,category 6.

Adapting the notation developed in Section 2 to this example we have:

$J = \{cat_1, cat_2, cat_3, cat_4, cat_5, cat_6\}$,

$I_{cat1} = \{weld_1, weld_2, weld_3, weld_4, weld_5, weld_6\}$,

$I_{cat2} = \{weld_1, weld_2, weld_3, weld_4, weld_5, weld_6\}$,

$I_{cat3} = \{weld_4, weld_5, weld_6\}$,

$I_{cat4} = \{weld_6\}$, $I_{cat5} = \{weld_6\}$, $I_{cat6} = \{weld_6\}$,

and

$$BreakSize_{cat_1}^{weld_1} \sim U[0.5, 1.625] \tag{4a}$$

$$BreakSize_{cat_1}^{weld_2} \sim U[0.5, 1.625] \tag{4b}$$

$$BreakSize_{cat_1}^{weld_3} \sim U[0.5, 1.625] \tag{4c}$$

$$BreakSize_{cat_1}^{weld_4} \sim U[0.5, 1.625] \tag{4d}$$

$$BreakSize_{cat_1}^{weld_5} \sim U[0.5, 1.625] \tag{4e}$$

$$BreakSize_{cat_1}^{weld_6} \sim U[0.5, 1.625] \tag{4f}$$

$$BreakSize_{cat_2}^{weld_1} \sim U[1.625, 1.7] \tag{4g}$$

$$BreakSize_{cat_2}^{weld_2} \sim U[1.625, 2] \tag{4h}$$

$$BreakSize_{cat_2}^{weld_3} \sim U[1.625, 2.5] \tag{4i}$$

$$BreakSize_{cat_2}^{weld_4} \sim U[1.625, 3] \tag{4j}$$

$$BreakSize_{cat_2}^{weld_5} \sim U[1.625, 3] \tag{4k}$$

$$BreakSize_{cat_2}^{weld_6} \sim U[1.625, 3] \tag{4l}$$

$$BreakSize_{cat_3}^{weld_4} \sim U[3, 3.8] \tag{4m}$$

$$BreakSize_{cat_3}^{weld_5} \sim U[3, 3.8] \tag{4n}$$

$$BreakSize_{cat_3}^{weld_6} \sim U[3, 7] \tag{4o}$$

$$BreakSize_{cat_4}^{weld_6} \sim U[7, 14] \tag{4p}$$

$$BreakSize_{cat_5}^{weld_6} \sim U[14, 31] \tag{4q}$$

$$BreakSize_{cat_6}^{weld_6} \sim U[31, 35]. \tag{4r}$$

Below we enumerate the first four steps of the procedure from Section 2.4 for this example system.

1. Assume $S = 1, N = 1$.

2. Sampled LOCA frequencies (using the fitted Johnson distributions) are given in Table 4. The right-most column of Table 4 computes the probability mass for each category according to equation (1).

3. Break frequency tables for each weld obtained from the bottom-up approach can be found in Tables 5-7. (For the full collection of location-specific frequency tables see Fleming et al. (2011).) Table 4 contains bins defining the break categories, as derived from Table 1. The associated categories for each break size are indicated in Tables 5-7.

   Using Tables 5-7 we compute weights for each weld and report results in Tables 8-10. To describe the derivation of these weights we begin with Table 8. The weld 1 frequency value in that table is the difference between the cumulative frequencies from the 0.5-inch row and the 1.7-inch row from Table 5. The weld 2 and weld 3 frequency values are the difference between the frequencies from the 0.5-inch row and the 2-inch row from Table 5. The weld 4, weld 5, and weld 6 frequencies are similarly the difference between the frequencies from the 0.5-inch rows and the 2-inch rows from Tables 6 and 7. Finally, we normalize the resulting values using equation (2) to compute the weights $w_{cat1}^{weld1}, \ldots, w_{cat1}^{weld6}$. Tables 9 and 10 contain the results of the analogous calculations for category 2 and category 3. There is no need to form the corresponding frequency values for category 4,...,category 6 because these categories only occur for weld 6, and hence these weights are simply 100%.

   Using equation (3) we now compute $P[cat_j \text{ at } weld_i]$ for each category-weld combination. The results are given in Table 11. We see that the sum of the distributed probabilities match the target probabilities.

4. We simulate break sizes for each weld within each category using the uniform distributions with the parameters specified in equation (4). The sample is shown in Table 12.

Finally, we note that our assumptions lead to a piece-wise linear CDF governing the break size for a given weld. For example, consider weld 6. The CDF of the break size for that weld has six pieces with the slopes determined by the $P[cat_j \text{ at } weld_6]$ values and break points at the $cat_j^{maxBreak}$ bin boundaries of 1.625, 3, 7, 14, and 31 inches, see Figure 4.

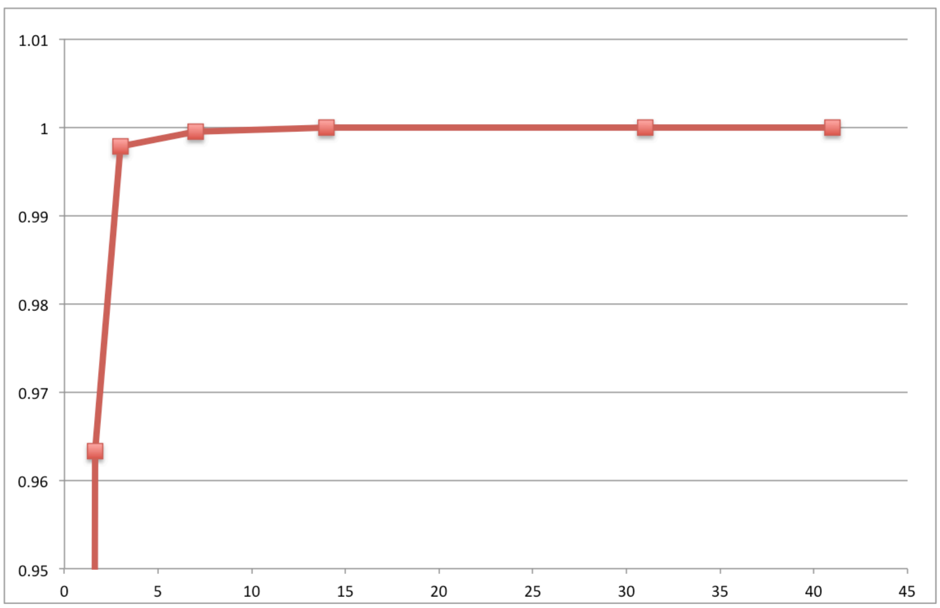


Figure 4: CDF of break size distribution for weld 6

Conclusion

In this document we present solutions to three problems:

1. How should we preserve the NUREG 1829 LOCA frequencies when distributing them across different locations (welds) in a nuclear power plant. The approach that we propose to take is rooted in combining the top-down and bottom-up approaches: We start with the NUREG-1829 frequencies and develop a way to distribute them to different locations proportionally to the frequencies estimated using the bottom-up approach. In this way, we maintain the NUREG-1829 frequencies overall but also allow for location-dependent differences.

2. The six break size categories (from the NUREG-1829 Table 1) represent six intervals. For a particular weld we need to be able to sample from the continuous interval of break size values. We propose to use linear interpolation which is equivalent to assigning equally likely probabilities within each break size category.

3. How to model the distribution of the LOCA frequencies. We propose to fit the Johnson distribution to the NUREG-1829 quantiles of 5%, 50%, and 95%.

In this document we do not discuss the different sampling techniques needed. We will provide their description and examples in a separate document.

Acknowledgements

We would like to thank Alexander Galenko for writing the optimization algorithm for the Johnson distribution and performing most of the computations we describe here.

Table 4: Sampled LOCA frequencies and corresponding probabilities

Failure Type	**Category**	**Break Size Bins** (in.)	**Frequency**	**Probability**
small	1	[0.5,1.625)	3.9E-03	9.64E-01
small	2	[1.625,3)	1.4E-04	3.50E-02
medium	3	[3,7)	3.4E-06	7.92E-04
medium	4	[7,14)	3.1E-07	7.64E-05
large	5	[14,31)	1.2E-08	2.77E-06
large	6	[31,41)	1.2E-09	3.08E-07

Table 5: Frequency tables for small welds from bottom-up approach

SMALL					
$weld_1$		$weld_2$		$weld_3$	
Small Bore		SIR		CVCS	
1		1.5		2	
1.414213562		2.121320344		2.828427125	
B-J		B-J		B-J	
VF, SC, D&C		D&C		TF, VF, D&C	
193		0		10	
X, Break Size (in.)	$F(LOCA \geq X)$	X, Break Size (in.)	$F(LOCA \geq X)$	X, Break Size (in.)	$F(LOCA \geq X)$
0.5 (cat1)	1.22E-07	0.5 (cat1)	1.1402E-08	0.5 (cat1)	4.2814E-08
0.75 (cat1)	7.18E-08	0.75 (cat1)	6.843E-09	0.75 (cat1)	2.5696E-08
1 (cat1)	5.00E-08	1 (cat1)	4.8541E-09	1 (cat1)	1.8227E-08
1.5 (cat1)	4.30E-09	1.5 (cat1)	3.072E-09	1.5 (cat1)	1.1536E-08
1.7 (cat2)	2.30E-09	2 (cat2)	1.6483E-09	2 (cat2)	6.0274E-09
				2.5 (cat2)	2.4179E-09

Table 6: Frequency tables for medium welds from bottom-up approach

MEDIUM			
$weld_4$		$weld_5$	
CVCS		Pressurizer	
4		3	
5.656854249		4.242640687	
BC		B-J	
TF, D&C		TF, D&C	
4		14	
X, Break Size (in.)	$F(LOCA \geq X)$	X, Break Size (in.)	$F(LOCA \geq X)$
0.5 (cat1)	7.9803E-08	0.5 (cat1)	4.5883E-08
0.75 (cat1)	4.7896E-08	0.75 (cat1)	2.7565E-08
1 (cat1)	3.3975E-08	1 (cat1)	1.9569E-08
1.5 (cat1)	2.1502E-08	1.5 (cat1)	1.24E-08
2 (cat2)	1.1235E-08	2 (cat2)	6.6408E-09
3 (cat3)	4.5068E-09	3 (cat3)	2.7541E-09
3.8 (cat3)	2.3397E-09	3.8 (cat3)	1.3018E-09

Table 7: Frequency tables for large welds from bottom-up approach

LARGE	
$weld_6$	
SG Inlet	
29	
41.01219331	
B-F	
SC, D&C	
4	
X, Break Size (in.)	$F(LOCA \geq X)$
0.5 (cat1)	1.9783E-06
1.5 (cat1)	4.5932E-07
2 (cat2)	3.4469E-07
3 (cat3)	2.3061E-07
4 (cat3)	1.5971E-07
6 (cat3)	9.5224E-08
6.75 (cat3)	8.1186E-08
14 (cat5)	3.3453E-08
20 (cat5)	1.8122E-08
29 (cat5)	9.5661E-09
31.5 (cat6)	8.3016E-09
35 (cat6)	5.2422E-09

Table 8: Category 1 weld weights in total failure frequency using bottom-up approach

Cat1	**weld1**	**weld2**	**weld3**	**weld4**	**weld5**	**weld6**	**Total**
Frequency	1.20E-07	9.75E-09	3.68E-08	6.86E-08	3.92E-08	1.63E-06	1.91E-06
Weight	6.30%	0.51%	1.93%	3.59%	2.06%	85.61%	100.00%

Table 9: Category 2 weld weights in total failure frequency using bottom-up approach

Cat2	**weld1**	**weld2**	**weld3**	**weld4**	**weld5**	**weld6**	**Total**
Frequency	2.30E-09	1.65E-09	6.03E-09	6.73E-09	3.89E-09	1.14E-07	1.35E-07
Weight	1.70%	1.22%	4.48%	5.00%	2.89%	84.71%	100.00%

Table 10: Category 3 weld weights in total failure frequency using bottom-up approach

Cat3	**weld4**	**weld5**	**weld6**	**Total**
Frequency	4.51E-09	2.75E-09	1.97E-07	2.04E-07
Weight	2.20%	1.35%	96.45%	100.00%

Table 11: Distributed LOCA probabilities among all welds

	weld1	**weld2**	**weld3**	**weld4**	**weld5**	**weld6**	**Total**	**Target**
Cat1	6.07E-02	4.93E-03	1.86E-02	3.46E-02	1.98E-02	8.25E-01	9.64E-01	9.64E-01
Cat2	5.97E-04	4.29E-04	1.57E-03	1.75E-03	1.01E-03	2.97E-02	3.50E-02	3.50E-02
Cat3	X	X	X	1.75E-05	1.07E-05	7.64E-04	7.92E-04	7.92E-04
Cat4	X	X	X	X	X	7.64E-05	7.64E-05	7.64E-05
Cat5	X	X	X	X	X	2.77E-06	2.77E-06	2.77E-06
Cat6	X	X	X	X	X	3.08E-07	3.08E-07	3.08E-07

Table 12: Sampled break sizes (inches) for all welds within each break category

Weld	1	2	3	4	5	6
Cat1	1.1	0.6	0.87	1.34	0.79	1.23
Cat2	1.69	1.9	2.1	2.9	1.75	2.36
Cat3	X	X	X	3.76	3.54	5.97
Cat4	X	X	X	X	X	9.67
Cat5	X	X	X	X	X	25.68
Cat6	X	X	X	X	X	32.67

References

Crenshaw, J. W. (2012, January). South Texas Project Units 1 and 2 Docket Nos. STN 50-499, Summary of the South Texas Project Risk-Informed Approach to Resolve Generic Safety Issue (GSI-191). Letter from John W. Crenshaw to USNRC.

EPRI (1999). Revised Risk-Informed In-Service Inspection Procedure. TR 112657 Revision B-A, Electric Power Research Institute, Palo Alto, CA.

Fleming, K. N., B. O. Lydell, and D. Chrun (2011, July). Development of LOCA Initiating Event Frequencies for South Texas Project GSI-191. Technical Report, KnF Consulting Services, LLC, Spokane, WA.

Johnson, N. (1949). Systems of Frequency Curves Generated by Methods of Translations. *Biometrika 36*, 149–176.

Letellier, B. (2011). Risk-Informed Resolution of GSI-191 at South Texas Project. Technical Report Revision 0, South Texas Project, Wadsworth, TX.

Mosleh, A. (2011, October). Technical Review of STP LOCA Frequency Estimation Methodology. Letter Report Revision 0, University of Maryland, College Park, MA.

Tregoning, R., P. Scott, and A. Csontos (2008, April). Estimating Loss-of-Coolant Accident (LOCA) Frequencies Through the Elicitation Process: Main Report (NUREG-1829). NUREG 1829, NRC, Washington, DC.