INL/CON-08-13778
PREPRINT

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ANS PSA 2008 Topical Meeting

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September 2008

ANS PSA 2008 Topical Meeting - Challenges to PSA during the nuclear renaissance
Knoxville, Tennessee, September 7–11, 2008, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2008)

ESTIMATING LOSS-OF-COOLANT ACCIDENT FREQUENCIES FOR THE STANDARDIZED PLANT ANALYSIS RISK MODELS

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ABSTRACT

The U.S. Nuclear Regulatory Commission maintains a set of risk models covering the U.S. commercial nuclear power plants. These standardized plant analysis risk (SPAR) models include several loss-of-coolant accident (LOCA) initiating events such as small (SLOCA), medium (MLOCA), and large (LLOCA). All of these events involve a loss of coolant inventory from the reactor coolant system. In order to maintain a level of consistency across these models, initiating event frequencies generally are based on plant-type average performance, where the plant types are boiling water reactors and pressurized water reactors. For certain risk analyses, these plant-type initiating event frequencies may be replaced by plant-specific estimates.

Frequencies for SPAR LOCA initiating events previously were based on results presented in NUREG/CR-5750, but the newest models use results documented in NUREG/CR-6928. The estimates in NUREG/CR-6928 are based on historical data from the initiating events database for pressurized water reactor SLOCA or an interpretation of results presented in the draft version of NUREG-1829. The information in NUREG-1829 can be used several ways, resulting in different estimates for the various LOCA frequencies. Various ways NUREG-1829 information can be used to estimate LOCA frequencies were investigated and this paper presents two methods for the SPAR model standard inputs, which differ from the method used in NUREG/CR-6928. In addition, results obtained from NUREG-1829 are compared with actual operating experience as contained in the initiating events database.

Key Words: loss-of-coolant accident, LOCA, initiating event, frequency

1 INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) maintains a set of risk models covering the U.S. commercial nuclear power plants. These standardized plant analysis risk (SPAR) models include several loss-of-coolant accident (LOCA) initiating events such as small (SLOCA), medium (MLOCA), and large (LLOCA). All of these events involve a loss of coolant inventory from the reactor coolant system (RCS). In order to maintain a level of consistency across these models, initiating event frequencies generally are based on plant-type average performance, where the plant types are boiling water reactors (BWRs) and pressurized water reactors (PWRs). For certain risk analyses, these plant-type initiating event frequencies may be replaced by plant-specific estimates.

The SPAR models also include other types of LOCA events, such as steam generator tube rupture (SGTR), very small LOCA, reactor coolant pump seal LOCA, stuck open relief valve, BWR steam line break outside containment, and interfacing system LOCA. Those are not covered in NUREG-1829 [1] except for SGTR and are not addressed in this paper.

Frequencies for SPAR LOCA initiating events previously were based on results presented in NUREG/CR-5750 [2], but the newest models use results documented in NUREG/CR-6928 [3]. The estimates in NUREG/CR-6928 are based on historical data from the initiating events database (IEDB)[4] for PWR SLOCA or an interpretation of results presented in the draft version of NUREG-1829 (LLOCA, MLOCA, and BWR SLOCA). The information in NUREG-1829 can be used several ways, resulting in different estimates for the various LOCA frequencies. After investigating the various ways NUREG-1829 information can be used to estimate LOCA frequencies, this paper presents two methods for the SPAR model standard inputs, which differ from the method used in NUREG/CR-6928. A final decision has not yet been made concerning which of the two methods to use. In addition, results obtained from NUREG-1829 are compared with actual historical experience as contained in the IEDB. A NUREG/CR report will document this work.

2 BACKGROUND

LOCA functional definitions used in the SPAR models are summarized in Table I. These functional definitions generally agree with those presented in WASH-1400 [5], NUREG-1150 [6], and NUREG/CR-5750. Depending upon the plant design characteristics (including the injection pump capacities) and the thermal-hydraulic codes used to estimate LOCA initial flow rates, these functional definitions can lead to varying LOCA break size ranges and associated initial flow rates. The SPAR models in general do not use plant-specific LOCA break sizes or associated flow rates for the various LOCA sizes. Plant-type average LOCA frequencies (for PWR and BWR categories) are used.

Three sources for LOCA break sizes are WASH-1400, NUREG-1150 (and NUREG/CR-5750), and NUREG-1829. Within WASH-1400, the historical break size ranges are 0.5 to 2.0 in. for SLOCA, 2.0 to 6.0 in. for MLOCA, and > 6.0 in. for LLOCA, However, there are several inconsistencies for BWRs. For example, the BWR SLOCA break size range is 0.5 to 2.0 in. in Table III 6-9 of WASH-1400, while the range is 0.6 to 2.6 in. (for liquid breaks) on p. I-55. Also, the MLOCA break size range is 2.0 to 6.0 in. (Table III 6-9 in WASH-1400) and 2.5 to 8.5 in. (liquid) (p. I-54).

The NUREG-1150 (and NUREG/CR-5750) results are similar to the WASH-1400 break sizes for PWRs, but NUREG-1150 also introduces associated makeup flow rates (100 to 1500 gpm for SLOCA and 1500 to 5000 gpm for MLOCA). For BWRs, NUREG-1150 defines SLOCA as < 1.0 in., MLOCA as 1.0 to 5.0 in., and LLOCA as > 5.0 in. These break size ranges were determined from a matrix of calculations that considered different break sizes and locations for the plants analyzed in NUREG-1150.

Table I. SPAR LOCA functional definitions

LOCA Category	PWR	BWR
SLOCA	The small LOCA initiating event is defined as a steam or liquid break in the RCS other than a steam generator tube rupture that exceeds normal charging flow. A safety injection signal will be generated to start the HPI [high-pressure injection] pumps. Secondary cooling is required to remove decay heat and cause the RCS to reach an equilibrium pressure which corresponds to the injection flow of the HPI pumps.	The small LOCA initiating event is defined as a steam or liquid break in the RCS where RCIC [reactor core isolation cooling] alone can maintain the reactor coolant inventory.
MLOCA	The medium LOCA initiating event is defined as a steam or liquid break that is large enough to remove decay heat without using the steam generators but small enough that RCS pressure is above the safety injection tanks and low pressure injection system shutoff pressure.	The medium LOCA initiating event is defined as a steam or liquid break that is too large to mitigate with the RCIC system and too small to sufficiently depressurize the reactor vessel for injection with low pressure systems.
LLOCA	The large LOCA initiating event is defined as a steam or liquid break that is large enough to rapidly depressurize the RCS pressure to a point below the low pressure injection and accumulator shutoff pressure.	The large LOCA initiating event is defined as a steam or liquid break that will rapidly depressurize the reactor vessel. High pressure injection systems will not have adequate flow rates or steam pressure to restore level and maintain cooling.

NUREG-1829 used the makeup flow rate definitions for LOCA sizes first introduced in NUREG-1150. However, NUREG-1829 used generic thermal-hydraulic models to determine the associated LOCA break sizes (Section 3.7 in NUREG-1829). The generic models may be more appropriate to use when general break size vs. flow rate relationships are required. However, these generic models generally resulted in smaller equivalent diameters for the higher flow rates (5000 gpm and higher) than the NUREG-1150 relationships. For instance, the MLOCA/LLOCA transition size using the generic models is approximately 3.0 in. (rather than 5.0 or 6.0 in. from WASH-1400 and NUREG-1150), as indicated in Tables 3.8 and 7.13 of NUREG-1829. However, when comparing results with other studies, NUREG-1829 and a recent summary paper [7] used 7.0 in. as the transition size between MLOCA and LLOCA (as indicated in Table 7-17,) in order to most closely match the 6.0-in transition size used in those prior studies. In the expert elicitation process used in NUREG-1829, the panel members provided frequency estimates based on break sizes for the LOCA categories listed in that report rather than based on the flow rates associated with a particular break size.

3 NUREG-1829 INFORMATION

NUREG-1829 provides the most recent estimates for LOCA frequencies for U.S. commercial nuclear power plants. That document presents exceedance frequencies for a range of LOCA category flow rates and associated break sizes, from >100 gpm to > 500,000 gpm (0.5 in. to 31 or 41 in. equivalent diameter), based on an expert elicitation process. The LOCA category exceedance frequencies include consideration of both piping and other passive components. NUREG-1829 presents a variety of results using different types of aggregation techniques and other sensitivities. A specific set of results is not recommended for all applications.

The results from NUREG-1829 chosen for the SPAR LOCA application are those using a geometric averaging of individual estimates. Those exceedance frequencies are reproduced as Table II (Tables 7.7 and 7.19 of that document). Geometric averaging is often used when individual positive estimates vary by more than an order of magnitude and a central tendency estimate is desired. Also, in such cases, arithmetic averaging results in higher mean estimates that are representative of the highest individual estimates. Geometric averaging is most consistent with the SPAR model philosophy of developing central tendency estimates for important input parameters (e.g., LOCA frequencies). Results are for the 25-year fleet average operation, rather than for end of license (40 years) or end of life (60 years), because the SPAR models focus on present performance, rather than potential future performance. Also, the PWR values do not include SGTR contributions because the SPAR models include SGTR as a separate initiating event. Note that the units for the NUREG-1829 exceedance frequencies are events per reactor calendar year (rcy) rather than reactor critical year (rcry). Also presented in the tables are the associated break sizes, using the thermal-hydraulic models described in that document.

Table II. LOCA exceedance frequencies (geometric average with error factor adjustment) without SGTR contributions (NUREG-1829, Table 7.17 for BWRs and Table 7.19 for PWRs, 25-year fleet average)

Reactor Type	LOCA Category	gpm	Effective Diameter (in.)	Exceedance Frequency (1/rcy)				
				5th	50th	Mean	95th	Error Factor (note a)
BWR	1	>100	0.50	3.3E-05	3.0E-04	6.5E-04	2.3E-03	7.7
	2	>1500	1.875	3.0E-06	5.0E-05	1.3E-04	4.8E-04	9.6
	3	>5000	3.25	6.0E-07	9.7E-06	2.9E-05	1.1E-04	11.3
	4	>25K	7.0	8.6E-08	2.2E-06	7.3E-06	2.9E-05	13.2
	5	>100K	18.0	7.7E-09	2.9E-07	1.5E-06	5.9E-06	20.3
	6	>500K	41.0	6.3E-12	2.9E-10	6.3E-09	1.8E-08	62.1
PWR	1	>100	0.50	6.8E-05	6.3E-04	1.9E-03	7.1E-03	11.3
	2	>1500	1.625	5.0E-06	8.9E-05	4.2E-04	2.4E-03	18.0
	3	>5000	3.0	2.1E-07	3.4E-06	1.6E-05	6.1E-05	17.9
	4	>25K	7.0	1.4E-08	3.1E-07	1.6E-06	6.1E-06	19.7
	5	>100K	14.0	4.1E-10	1.2E-08	2.0E-07	5.8E-07	48.3
	6	>500K	31.0	3.5E-11	1.2E-09	2.9E-08	8.1E-08	67.5

a. The error factor column is not in the NUREG-1829 table. It is defined as $95^{th}/50^{th}$.

Table II also presents the 5th, 50th, and 95th percentiles associated with each LOCA category mean exceedance frequency. These percentiles were estimated from the individual panelists' inputs, which included 5th, 50th, and 95th percentile estimates. The specifics of combining individual panelist estimates to generate an overall percentile estimate are discussed in Section 5 of NUREG-1829. The authors state that these percentiles do not imply any particular overall LOCA frequency distribution for each LOCA category.

4 SPAR LOCA FREQUENCY DETERMINATION

Two methods are presented in this paper for determining SPAR LOCA frequencies using information presented in NUREG-1829 and from operating experience. Both approaches follow these steps:

1. Identify generic or plant-specific break size ranges for each of the SPAR LOCA categories
2. Interpolate between NUREG-1829 table entries as needed to obtain mean frequencies for each LOCA break size range
3. Use the percentile information in NUREG-1829 (provided for each table entry) to determine appropriate uncertainty distributions for each SPAR LOCA frequency
4. Use recent operating experience as appropriate to update the resulting frequency distributions.

Each of these steps is discussed below in detail for method 1. Method 2 is summarized later in this paper.

<u>Method 1</u>

The method 1 approach to identifying appropriate LOCA break sizes for BWRs and PWRs is to average plant-specific LOCA size ranges that have been developed for each plant type. A limited set of such information was available for this study, based on recent licensee risk assessment documentation submitted to NRC as part of the SPAR model enhancement effort. Results are summarized in Table III. Geometric averages were obtained for the BWR and PWR pipe break transition sizes. (Arithmetic average results are similar and do not affect the rounded results.) Based on this limited survey, the BWR SLOCA/MLOCA transition size is 1.09 in., which was rounded to 1.0 in. Also, the MLOCA/LLOCA transition size is 4.97 in., which was rounded to 5.0 in. Also, the PWR splits are 2.22 and 6.16 in., respectively, which were rounded to 2.0 and 6.0 in.

It is recognized that these plant-type break size ranges might not agree with a specific plant's break size ranges. However, the philosophy of the basic SPAR models is to use generic information to represent initiating events and plant-specific design and operational models to examine risks for individual plants. For specific analyses, these plant-type LOCA break size ranges could be replaced by plant-specific break sizes if available. The methods outlined in this document also apply to the generation of plant-specific LOCA frequencies.

The mean exceedance frequencies for BWR and PWR LOCA categories (after subtracting SGTR contributions) from NUREG-1829 are listed in Table II. Given BWR LOCA break size ranges of 0.5 to 1.0 in. for SLOCA, 1.0 to 5.0 in. for MLOCA, and > 5.0 in. for LLOCA, interpolation is required for the > 1.0-in. and > 5.0-in. break sizes. The approach chosen for interpolation is to use power law fits between adjacent data points in Table II. The power law fit is of the form

$$y = ax^b , \tag{1}$$

where y = exceedance frequency (1/rcy)
x = effective break size (diameter, in.)
a = curve fit constant
b = curve fit constant.

Table III. Plant-specific LOCA size ranges from selected

Licensee Risk Assessment Document	Plant Type	# Plants	Break Size Ranges (in., equivalent diameter)					
			Small LOCA		Medium LOCA		Large LOCA	
			Low	High	Low	High	Low	High
1	BWR	3	100 gpm	1.00	1.00	5.00	5.00	
2	BWR	1		1.00	1.00	6.00	6.00	
3	BWR	2	0.50	1.20	1.20	5.90	5.90	
4	BWR	1		1.50	1.50	4.00	4.00	
5	BWR	1	100 gpm	0.86	0.86	4.30	4.30	
6	PWR	1	0.38	1.90	1.90	4.30	4.30	36.00
7	PWR	2		2.00	2.00	6.00	6.00	
8	PWR	1	0.38	3.00	3.00	5.00	5.00	
9	PWR	1	100 gpm	2.00	2.00	6.00	6.00	
10	PWR	3	0.38	2.35	2.35	6.00	6.00	
11	PWR	1	0.38	1.50	1.50	13.00	13.00	
12	PWR	2	0.50	2.00	2.00	6.00	6.00	
13	PWR	1	0.50	2.00	2.00	6.00	6.00	29.00
14	PWR	2	0.50	2.00	2.00	6.00	6.00	
15	PWR	1	0.90	5.00	5.00			
16	PWR	2	1.00	2.00	2.00	6.00	6.00	
Geometric Average, BWRs			0.50	1.09		4.97		
Geometric Average, PWRs			0.51	2.22		6.43		

Note - Blank entries were ignored, and "100 gpm" entries were assumed to be 0.5 in.

Given two adjacent data points, the solution for b is the following:

$$b = \ln\left(\frac{y_1}{y_2}\right) \bigg/ \ln\left(\frac{x_1}{x_2}\right). \tag{2}$$

Then the solution for a is the following, given b:

$$a = y_1 / x_1^{\ b} = y_2 / x_2^{\ b}. \tag{3}$$

For BWRs, interpolation to obtain a mean exceedance frequency for > 1.0 in. uses the data points (0.50 in., 6.50E-4/rcy) and (1.875 in., 1.30E-4/rcy) from Table II. Therefore, *b* = -1.22 and *a* = 2.79E-4. This results in an exceedance frequency of 2.79E-4/rcy for a break size of > 1.0 in. Similarly, interpolation to obtain an exceedance frequency for > 5.0 in. uses the data points (3.25 in., 2.90E-5/rcy) and (7.0 in., 7.30E-6/rcy). Therefore, *b* = -1.80 and *a* = 2.41E-4. This results in an exceedance frequency of 1.33E-5/rcy for a break size of > 5.0 in. The exceedance frequencies are summarized below:

> 0.5 in. – 6.50E-4/rcy
> 1.0 in. – 2.79E-4/rcy
> 5.0 in. – 1.33E-5/rcy.

Therefore, the BWR LOCA category mean frequencies are the following:

SLOCA (0.5 to 1.0 in.) = 6.50E-4/rcy – 2.79E-4/rcy = 3.71E-4/rcy
MLOCA (1.0 to 5.0 in.) = 2.79E-4/rcy – 1.33E-5/rcy = 2.66E-4/rcy
LLOCA (> 5.0 in.) = 1.33E-6/rcy.

Because the SPAR initiating events have units of events per rcry, these results must be converted to 1/rcry units. Assuming plants are critical 90% of the time on average (the same assumption used in NUREG/CR-6928) and that these LOCA estimates were based on critical operation conditions, the results must be multiplied by the factor (1 rcy)/(0.9 rcry). Converting to 1/rcry units for SPAR, the BWR SPAR LOCA mean frequencies are the following:

SLOCA (0.5 to 1.0 in.) = (3.71E-4/rcy)(1 rcy)/(0.9 rcry) = 4.12E-4/rcry
MLOCA (1.0 to 5.0 in.) = (2.66E-4/rcy)(1 rcy)/(0.9 rcry) = 2.96E-4/rcry
LLOCA (> 5.0 in.) = (1.33E-5/rcy)(1 rcy)/(0.9 rcry) = 1.48E-5/rcry.

Following the same process for PWRs, the PWR SPAR LOCA mean frequencies are the following:

SLOCA (0.5 to 2.0 in.) = (1.76E-3/rcy)(1 rcy)/(0.9 rcry) = 1.96E-3/rcry
MLOCA (2.0 to 6.0 in.) = (1.37E-4/rcy)(1 rcy)/(0.9 rcry) = 1.52E-4/rcry
LLOCA (> 6.0 in.) = (2.43E-6/rcy)(1 rcy)/(0.9 rcry) = 2.70E-6/rcry.

To obtain uncertainty distributions for these frequencies, the NUREG-1829 percentile information (5^{th}, 50^{th}, and 95^{th} percentiles) and the mean for each of the entries in its Tables 7.7, 7.17, 7.18, and 7.19 were used. None of the table entries in NUREG-1829 can be used directly to determine uncertainty distributions for the SPAR LOCA frequencies. This is because either interpolation is needed (to determine the > 1.0 in. and > 5.0 in. exceedance frequencies for BWRs and > 2.0 in. and > 6.0 in. for PWRs) or one exceedance frequency needs to be subtracted from another, or both. Both types of operations affect the uncertainty.

Once the interpolations described above were performed, the uncertainty distribution for a difference required some care. A convenient assumption is that mutually exclusive classes of events such as SLOCAs and MLOCAs have statistically independent uncertainty distributions. This assumption of independence allowed means and variances of various frequencies to be combined in a mathematically correct way. The variance associated with an exceedance break size was determined from the median and mean, assuming a lognormal distribution. (Means and medians for break sizes not in Table II were obtained using the interpolation process described above.) Subtracting one exceedance mean frequency from another (and subtracting the associated variances) produced a mean and variance for the break size range under consideration. Using the resulting mean and variance, a lognormal distribution was determined, which was then approximated by a gamma distribution with matching mean and error factor. (This step is iterative, varying the alpha parameter of the gamma distribution, while holding the mean constant, until the required error factor is achieved.) Finally, these were converted from per rcy to per rcry. To convert the gamma distributions to rcry units, the mean is multiplied by the factor (1.0 rcy)/(0.9 rcry) = 1.11 rcy/rcry. The α parameter remains the same, but β is divided by 1.11. Distributions for LOCA categories are presented in Tables IV (BWRs) and V (PWRs).

Following the approach used in NUREG/CR-6928, the LOCA frequencies derived from NUREG-1829 were compared with operational experience from U.S. commercial nuclear power plants over the period 1988 – 2007 as contained in the IEDB. (In contrast, NUREG/CR-6928 used data only through 2002.) The period 1988 – 2007 is limited relative to MLOCAs and LLOCAs because of their low estimated frequencies and lack of operational events. However, it is long enough to provide potentially reasonable estimates for SLOCAs. The BWR operational experience over 1988 – 2007 indicates no SLOCAs and 574.5 BWR rcry. A mean frequency was generated from these data using a Bayesian update of the Jeffreys noninformative prior, as explained in NUREG/CR-6928. The mean frequency is

$$Mean = \frac{(0.5+0)}{574.5rcry} = 8.70E-4/rcry\,. \tag{4}$$

Table IV. Method 1 gamma distributions for SPAR BWR LOCA frequencies derived from NUREG-1829 (1/rcry units)

LOCA Category	Break Size Range (equivalent diameter, in.)	Gamma Distribution						
		α	B (rcry)	5th (1/rcry)	50th (1/rcry)	Mean (1/rcry)	95th (1/rcry)	Error Factor
SLOCA	0.5 to 1.0 in.	0.391	9.498E+02	3.65E-07	1.45E-04	4.12E-04	1.72E-03	11.9
MLOCA	1.0 to 5.0 in.	0.468	1.583E+03	8.10E-07	1.27E-04	2.96E-04	1.16E-03	9.2
LLOCA	> 5.0 in.	0.384	2.585E+04	1.16E-08	5.13E-06	1.49E-05	6.26E-05	12.2

Table V. Method 1 gamma distributions for SPAR PWR LOCA frequencies derived from NUREG-1829 (1/rcry units)

LOCA Category	Break Size Range (equivalent diameter, in.)	Gamma Distribution						
		α	B (rcry)	5th (1/rcry)	50th (1/rcry)	Mean (1/rcry)	95th (1/rcry)	EF
SLOCA	0.5 to 2.0 in.	0.382	1.952E+02	1.48E-06	6.72E-04	1.96E-03	8.26E-03	12.3
MLOCA	2.0 to 6.0 in.	0.303	1.999E+03	1.78E-08	3.76E-05	1.52E-04	6.91E-04	18.4
LLOCA	> 6.0 in.	0.295	1.091E+05	2.48E-10	6.41E-07	2.70E-06	1.24E-05	19.4

In comparison, the mean frequency derived from NUREG-1829 is 4.12E-4/rcry (Table IV). Because the operational experience over 1988 – 2007 does not include any SLOCAs, its mean frequency estimate may be conservatively high. Therefore, the frequency estimate derived from NUREG-1829 was selected for the BWR SLOCA.

Operational experience over 1988 – 2007 from U.S. PWRs indicates no SLOCAs and 1179.0 PWR rcry.[1] The mean frequency using these data is

$$Mean = \frac{(0.5+0)}{1179.0rcry} = 4.24E-4/rcry\ . \qquad (5)$$

This result is lower than the estimate derived from NUREG-1829, 1.96E-3/rcry (Table V). In this case, the operational experience, even though there were no events, results in a lower estimate because of the larger number of rcry compared with the BWR case. The operational experience therefore supports a lower estimate for the PWR SLOCA frequency. However, NUREG-1829 indicates that an emerging issue, primary water stress corrosion cracking (PWSCC), caused the expert elicitation participants to increase their PWR SLOCA (and MLOCA) frequency estimates above what operational experience indicated. Also, NUREG-1829 indicates that operational experience may not be applicable because this is an emerging issue (causing the SLOCA frequency to not be constant over the historical period).

To incorporate both the NUREG-1829 derived PWR SLOCA frequency estimate reflecting concerns about PWSCC and more recent operating experience, a Bayesian update process was used. The NUREG-1829 frequency distribution (Table V) was used as the prior distribution. That distribution is gamma (0.382, 195.2 rcry). Because the expert elicitation process in NUREG-1829 occurred in 2003 through February 2004, the experts' knowledge base (and corresponding operational experience) reflected information up through approximately 2003. Operational experience for PWR SLOCA for 2004 – 2007 indicates no events and 252.1 rcry. The Bayesian update results in a posterior mean [8] of

$$Mean_{Posterior} = (0.382+0)/(195.2rcry + 252.1rcry) = 8.54E-4/rcry\ . \qquad (6)$$

This mean lies between the NUREG-1829 estimate of 1.96E-3/rcry and the operational experience (1988 – 2007) estimate of 4.24E-4/rcry. The posterior distribution is gamma (0.382, 447.3 rcry). Because PWSCC concerns also influenced the NUREG-1829 MLOCA frequency estimate, that distribution was also updated in a similar manner. Table VI summarizes the LOCA frequency distributions with these changes for PWR SLOCA and MLOCA. The NUREG-1829 PWR SLOCA and MLOCA distributions in Table V might be more appropriate than these updated distributions for plants that are particularly sensitive to PWSCC concerns (e.g., higher component temperatures or susceptible material heats).

Method 2

The method 2 approach differs from method 1 only in the selection of the LOCA size ranges. This method directly uses the LOCA size ranges in NUREG-1829 for each plant-type

[1] NUREG-1829 lists one SLOCA at PWRs in 1991, described in Licensee Event Report (LER) 2871991008. A review of the LER indicates that the average leakage rate while the reactor was pressurized (a period close to 16 hours) was approximately 80 gpm. However, for a short period around two hours after initiation of the event, the leakage rate was approximately 130 gpm. The IEDB considers this event to be a very small LOCA (< 100 gpm) rather than a SLOCA because the initial and average leakage rate was < 100 gpm and because the normal makeup pump was able to keep up with the leakage without an emergency safety features signal being generated. However, at one point the leakage rate did rise above 100 gpm, so this event exceeded the SLOCA threshold flow rate and it was decided to conservatively characterize this event as a SLOCA in NUREG-1829. Given one SLOCA over 1988 – 2007, the result using Eq. 5 would be 1.27E-3/rcry.

(BWR or PWR) and is appropriate when plant-specific break size and flow rate relationships are not available. The BWR LOCA size ranges in NUREG-1829 are 0.5 to 1.875 in. for SLOCA, 1.875 to 3.25 in. for MLOCA, and > 3.25 in. for LLOCA. The NUREG-1829 PWR LOCA size ranges are 0.5 to 1.625 in. for SLOCA, 1.625 to 3.0 in. for MLOCA, and > 3.0 in. for LLOCA. Following the same approach described above but using these LOCA transition sizes, the results are listed in Table VII.

Method 2 NUREG-1829 LOCA transition sizes are smaller than those used in method 1 that were obtained from a review of selected licensee risk assessments. The mean frequencies determined using method 1 and 2 are similar for BWR SLOCA and MLOCA and PWR SLOCA. However, the mean frequencies determined using method 2 are significantly higher than those determined using method 1 for BWR LLOCA and PWR MLOCA and LLOCA. The decision on which method to use in the SPAR models has not yet been finalized.

Table VI. Method 1 gamma distributions for SPAR LOCA frequencies after modification to PWR SLOCA and MLOCA

Plant Type	LOCA Category	Break Size Range (equiv. diameter, in.)	Gamma Distribution						
			α	β (rcry)	5th (1/rcry)	50th (1/rcry)	Mean (1/rcry)	95th (1/rcry)	Source
BWR	SLOCA	0.5 to 1.0 in.	0.473	7.869E+02	1.75E-06	2.60E-04	6.01E-04	2.36E-03	NUREG-1829
BWR	MLOCA	1.0 to 5.0 in.	0.416	3.767E+03	1.48E-07	4.19E-05	1.10E-04	4.53E-04	NUREG-1829
BWR	LLOCA	> 5.0 in.	0.378	3.532E+04	7.49E-09	3.63E-06	1.07E-05	4.53E-05	NUREG-1829
PWR	SLOCA	0.5 to 2.0 in.	0.382	4.473E+02	6.44E-07	2.93E-04	8.54E-04	3.60E-03	Bayesian Update
PWR	MLOCA	2.0 to 6.0 in.	0.303	2.251E+03	1.58E-08	3.33E-05	1.35E-04	6.14E-04	Bayesian Update
PWR	LLOCA	> 6.0 in.	0.295	1.091E+05	2.48E-10	6.41E-07	2.70E-06	1.24E-05	NUREG-1829

5 COMPARISON WITH PREVIOUS RESULTS

The LOCA frequencies for the SPAR models obtained using methods 1 and 2 can be compared directly with several previous sources. Previously the SPAR models used LOCA frequencies from NUREG/CR-5750, and the most recent updates came from NUREG/CR-6928. Comparisons with both of these references are presented in Table VIII. The main differences are for BWR LLOCA and PWR MLOCA and LLOCA. The BWR LLOCA frequency determined using method 2 is greater than the frequencies obtained using method 1 and from NUREG/CR-6928. However, it agrees well with the NUREG/CR-5750 results. Method 2 results in a significantly higher PWR LLOCA frequency than the other estimates.

Table VII. Method 2 gamma distributions for SPAR LOCA frequencies after modification to PWR SLOCA and MLOCA

Plant Type	LOCA Category	Break Size Range (equiv. diameter, in.)	Gamma Distribution						
			α	β (rcry)	5th (1/rcry)	50th (1/rcry)	Mean (1/rcry)	95th (1/rcry)	Source
BWR	SLOCA	0.5 to 1.875 in.	0.460	7.962E+02	1.43E-06	2.43E-04	5.78E-04	2.29E-03	NUREG-1829
BWR	MLOCA	1.875 to 3.25 in.	0.386	3.440E+03	9.11E-08	3.90E-05	1.12E-04	4.72E-04	NUREG-1829
BWR	LLOCA	> 3.25 in.	0.402	1.248E+04	3.45E-08	1.18E-05	3.22E-05	1.34E-04	NUREG-1829
PWR	SLOCA	0.5 to 1.625 in.	0.357	4.692E+02	3.49E-07	2.40E-04	7.61E-04	3.29E-03	Bayesian Update
PWR	MLOCA	1.625 to 3.0 in.	0.300	9.204E+02	3.49E-08	7.95E-05	3.26E-04	1.49E-03	Bayesian Update
PWR	LLOCA	> 3.0 in.	0.306	1.721E+04	2.28E-09	4.47E-06	1.78E-05	8.08E-05	NUREG-1829

Table VIII. Comparison of suggested SPAR LOCA frequencies with previous estimates

Reactor Type	Initiating Event	Mean Frequency (1/rcry)			
		This Report (Method 1)	This Report (Method 2)	NUREG/ CR-6928	NUREG/ CR-5750
BWR	SLOCA	6.01E-04	5.78E-04	5.00E-04	5.0E-04
	MLOCA	1.10E-04	1.12E-04	1.04E-04	4.0E-05
	LLOCA	1.07E-05	3.22E-05	6.78E-06	3.0E-05
PWR	SLOCA	8.54E-04	7.61E-04	5.77E-04	5.0E-04
	MLOCA	1.35E-04	3.26E-04	5.10E-04	4.0E-05
	LLOCA	2.70E-06	1.78E-05	1.33E-06	5.0E-06

6 CONCLUSIONS

New SLOCA, MLOCA, and LLOCA frequency distributions have been generated for the SPAR models using two different sets of LOCA transition sizes. These new distributions were derived from information in NUREG-1829. A Bayesian update process was used to modify the NUREG-1829 estimates for PWR SLOCA and MLOCA, based on recent operating experience. A final decision on which set of LOCA transition sizes to use in the SPAR models has not been made at this time. For certain plant-specific analyses, alternative break size ranges may be more appropriate. The process outlined in this paper can be used to generate plant-specific LOCA frequencies if plant-specific break size ranges are identified. Finally, the NUREG-1829 PWR SLOCA and MLOCA distributions in Table V might be more appropriate than these updated distributions for plants that are particularly sensitive to PWSCC concerns (e.g., higher component temperatures or susceptible material heats).

7 ACKNOWLEDGMENTS

This work was sponsored by the NRC, Office of Nuclear Regulatory Research. The initial request for such work came from R. Bernhard. Valuable comments were provided by M. Azarm, L. Abramson, R. Tregoning, and D. Kelly. Suggestions in this paper are solely those of the authors and not those of the NRC.

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