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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 suggests one particular method for the SPAR model standard inputs, which differs from the method used in NUREG/CR-6928. In addition, results obtained from NUREG-1829 are compared with actual historical 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 suggests one particular method for the SPAR model standard inputs, which differs from the method used in NUREG/CR-6928. 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.

Some examples of LOCA break sizes are presented in Table II. 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 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 the flow rate definitions listed above.

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 different thermal-hydraulic models to determine the associated LOCA break sizes (Section 3.7 in NUREG-1829). These models generally resulted in smaller equivalent diameters associated with the higher flow rates (5000 gpm and higher) compared with NUREG-1150. This resulted in the MLOCA/LLOCA split being 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. However, when comparing results with other studies, NUREG-1829 uses 7.0 in. as the split between MLOCA and LLOCA (as indicated in Table 7-17,). That same MLOCA/LLOCA split was used in a recent conference paper authored by one of the experts involved in estimating the NUREG-1829 frequencies [7]. In the expert elicitation process used in NUREG-1829, the panel members generally provided frequency estimates based on pipe and break sizes for the LOCA categories listed in that report (rather than the associated flow rates).

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.

Table II. Examples of LOCA break size ranges

LOCA Category and Plant Type	WASH-1400	NUREG-1150 and NUREG/CR-5750	NUREG-1829
BWR SLOCA	0.5 to 2.0 in. (Table III 6-9) 0.6 to 2.6 in. (liquid) or 1.0 to 4.7 in. (steam) (p. I-55) Flow rates not indicated	Less than 0.004 sq. ft. liquid (~1 in. diameter) or less than 0.05 sq. ft. steam (~4 in.) (NUREG/CR-4550, Vol. 1, Rev. 1, p. 3-23 and NUREG/CR-5750, p. A-4) Can be mitigated by coolant injection systems with 100 to 1500 gpm (NUREG/CR-4550, Vol. 1, Rev. 1, p. 3-4)	0.5 to 1.875 in. (using 100 to 1500 gpm definition) (Section 7.7, Table 7.17) 0.5 to 1.875 in. (comparing with historical studies) (Section 7.9, Table 7.20)
PWR SLOCA	0.5 to 2.0 in. equivalent diameter (Table III 6-9 and p. I-45) Flow rates not indicated	0.5 to 2.0 in. (NUREG/CR-4550, Vol. 3, Rev. 1, Part 1, p. 4.3-2) Can be mitigated by coolant injection systems with 100 to 1500 gpm (NUREG/CR-4550, Vol. 1, Rev. 1, p. 3-4)	0.5 to 1.625 in. (using 100 to 1500 gpm definition) (Section 7.7, Table 7.17) 0.5 to 1.625 in. (comparing with historical studies) (Section 7.9, Table 7.20)
BWR MLOCA	2.0 to 6.0 in. (Table III 6-9) 2.5 to 8.5 in (liquid) or 4.7 to 6.0 in. (steam) (p. I-54) Flow rates not indicated	0.004 to 0.10 sq. ft. liquid (~1.0 to 5.0 in. diameter) or 0.05 to 0.10 sq. ft. steam (~4.0 to 5.0 in.) (NUREG/CR-4550, Vol. 1, Rev. 1, p. 3-23 and NUREG/CR-5750, P. A-5) Can be mitigated by coolant injection systems with 1500 to 5000 gpm (NUREG/CR-4550, Vol. 1, Rev. 1, p. 3-4)	1.875 to 3.25 in. (using 1500 to 5000 gpm definition) (Section 7.7, Table 7.17) 1.875 to 7.0 in. (comparing with historical studies) (Section 7.9, Table 7.20)
PWR MLOCA	2.0 to 6.0 in. (Table III 6-9 and p. I-44) Flow rates not indicated	2.0 to 6.0 in. (NUREG/CR-4550, Vol. 3, Rev. 1, Part 1, p. 4.3-2) Can be mitigated by coolant injection systems with 1500 to 5000 gpm (NUREG/CR-4550, Vol. 1, Rev. 1, p. 3-4)	1.625 to 3.0 in. (using 1500 to 5000 gpm definition) (Section 7.7, Table 7.17) 1.625 to 7.0 in. (comparing with historical studies) (Section 7.9, Table 7.20)
BWR LLOCA	> 6.0 in. (Table III 6-9) > 0.40 sq. ft. (> 8.5 in.) (p. I-51) Flow rates not indicated	> 0.10 sq. ft. (> ~5.0 in. diameter) (NUREG/CR-4550, Vol. 1, Rev. 1, p. 3-23 and NUREG/CR-5750, p. A-5)	> 3.25 in. (using > 5000 gpm definition) (Section 7.7, Table 7.17) > 7.0 in. (comparing with historical studies) (Section 7.9, Table 7.20)
PWR LLOCA	> 6.0 in. (Table III 6-9 and p. I-42) Flow rates not indicated	> 6.0 in. (NUREG/CR-4550, Vol. 3, Rev. 1, Part 1, p. 4.3-2)	> 3.0 in. (using > 5000 gpm definition) (Section 7.7, Table 7.17) > 7.0 in. (comparing with historical studies) (Section 7.9, Table 7.20)

The results from NUREG-1829 chosen for the SPAR LOCA application are those using a geometric averaging of individual responses. Those exceedance frequencies are reproduced as Table III (Tables 7.7 and 7.19 of that document). Geometric averaging is considered to be most applicable to the SPAR model philosophy of representing best estimate LOCA performance. (Geometric averaging is often used when individual positive estimates vary significantly and a central tendency estimate is desired. Also, in such cases, arithmetic averaging results in higher mean estimates that are significantly impacted by individual outlier estimates.) 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 III 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

The preferred approach for determining SPAR LOCA frequencies using information presented in NUREG-1829 and from historical evidence follows these steps:

1. Identify appropriate 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. Compare the resulting distributions with historical evidence from the IEDB and choose the most appropriate result.

Each of these steps is discussed below.

From Table II it appears that an appropriate plant-type break size range for BWR SLOCA is 0.5 to approximately 2.0 in. (The upper limit ranges from 1.0 to 2.6 in. in the table, and 2.0 in. lies within this range.) Also, an appropriate break size range for BWR MLOCA is approximately 2.0 to 6.0 in. (The upper limit ranges from 3.2 to 8.5 in. in the table, and 6.0 in. lies within this range.) Finally, the BWR LLOCA range is approximately > 6.0 in. Another way to estimate plant-type average break size ranges for BWRs might be to review plant-specific break size ranges determined by plant-specific LOCA spectrum analyses performed using best estimate inputs. However, such information was not available for this effort and may not be available for many of the plants. The PWR break size ranges are similar, based on a review of Table II.

Table III. 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)				
				5%	50%	Mean	95%	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%/50%.

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 initiating event and basic event current performance at the plant-type or industry-average level, but with plant-specific design and operational models. For specific analyses, these plant-type LOCA break size ranges might need to be replaced by plant-specific break sizes if available. The method outlined in this document also applies 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 III. Given LOCA break size ranges of 0.5 to 2.0 in. for SLOCA, 2.0 to 6.0 in. for MLOCA, and > 6.0 in. for LLOCA, interpolation is required for the > 2.0-in. and > 6.0-in. break sizes. The approach chosen for interpolation is to use power law fits between adjacent data points in Table III. 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.

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

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

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

$$a = y / x^b . \qquad (3)$$

For BWRs, interpolation to obtain a mean exceedance frequency for > 2.0 in. uses the data points (1.875 in., 1.30E-4/rcy) and (3.25 in., 2.90E-5/rcy) from Table III. Therefore, *b* = -2.73 and *a* = 7.23E-4. This results in an exceedance frequency of 1.09E-4/rcy for a break size of > 2.0 in. Similarly, interpolation to obtain an exceedance frequency for > 6.0 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* = 2.42E-4. This results in an exceedance frequency of 9.62E-6/rcy for a break size of > 6.0 in. The exceedance frequencies are summarized below:

> 0.5 in. – 6.50E-4/rcy
> 2.0 in. – 1.09E-4/rcy
> 6.0 in. – 9.62E-6/rcy.

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

SLOCA (0.5 to 2.0 in.) = 6.50E-4/rcy - 1.09E-4/rcy = 5.41E-4/rcy
MLOCA (2.0 to 6.0 in.) = 1.09E-4/rcy - 9.62E-6/rcy = 9.94E-5/rcy
LLOCA (> 6.0 in.) = 9.62E-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 2.0 in.) = (5.41E-4/rcy)(1 rcy)/(0.9 rcry) = 6.01E-4/rcry
MLOCA (2.0 to 6.0 in.) = (9.94E-5/rcy)(1 rcy)/(0.9 rcry) = 1.10E-4/rcry
LLOCA (> 6.0 in.) = (9.62E-6/rcy)(1 rcy)/(0.9 rcry) = 1.07E-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. NUREG-1829 used split lognormal distributions to determine the percentile information presented in those tables, obtained from matching these distributions to the set of estimates provided by the experts. 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 > 2.0 in. and > 6.0 in. exceedance frequencies) 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. The most reasonable approach was to assume 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. Corresponding to the resulting means and variances, lognormal distributions were found, which were then approximated by gamma distributions with matching means and error factors. 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. Resulting distributions for LOCA categories are presented in Tables IV (BWRs) and V (PWRs).

Table IV. 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	β (rcry)	5% (1/rcry)	50% (1/rcry)	Mean (1/rcry)	95% (1/rcry)	Error Factor
SLOCA	0.5 to 2.0 in.	0.473	7.869E+02	1.75E-06	2.60E-04	6.01E-04	2.36E-03	9.1
MLOCA	2.0 to 6.0 in.	0.416	3.767E+03	1.48E-07	4.19E-05	1.10E-04	4.53E-04	10.8
LLOCA	> 6.0 in.	0.378	3.532E+04	7.49E-09	3.63E-06	1.07E-05	4.53E-05	12.5

Table V. 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	β (rcry)	5% (1/rcry)	50% (1/rcry)	Mean (1/rcry)	95% (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

Following the approach used in NUREG/CR-6928, the LOCA frequencies derived from NUREG-1829 were compared with historical evidence 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 historical events. However, it is long enough to provide potentially reasonable estimates for SLOCAs. The BWR historical 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

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

In comparison, the mean frequency derived from NUREG-1829 is 6.10E-4/rcry (Table 9). These two estimates agree reasonably well. However, because the historical evidence 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.

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

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

This result is lower than the estimate derived from NUREG-1829, 1.96E-3/rcry (Table V). In this case, the historical evidence, even though there were no events, results in a lower estimate because of the larger number of rcry compared with the BWR case. Therefore, the historical evidence is sufficient to provide 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 historical evidence indicated. Also, NUREG-1829 indicates that historical evidence 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 historical evidence, 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 historical evidence) reflected information up through approximately 2002. Historical evidence for PWR SLOCA for 2003 – 2007 indicates no events and 313.3 rcry. The Bayesian update results in a posterior mean [8] of

$$Mean_{Posterior} = (0.382+0)/(195.2rcry + 313.3rcry) = 7.51E-4/rcry\ . \tag{6}$$

This mean lies between the NUREG-1829 estimate of 1.96E-3/rcry and the historical evidence (1988 – 2007) estimate of 4.24E-4/rcry. The posterior distribution is gamma (0.382, 508.5 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. For plant-specific analyses where PWSCC is of concern, the NUREG-1829 distributions should be used for PWR SLOCA and MLOCA instead of the SPAR suggested distributions.

Various sensitivity analyses were also performed. Those studies addressed issues such as the use of different SLOCA/MLOCA and MLOCA/LLOCA break size splits, use of 25-year

[1] NUREG-1829 lists one SLOCA at PWRs, 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 20 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.

estimates from NUREG-1829 rather than end of license (40-year) estimates, and use of the Bayesian update value for PWR SLOCA rather than the NUREG-1829 estimate. None of these are explicitly incorporated into the uncertainty distributions presented in Table VI. Results indicated that the use of different break size splits can significantly affect the results for PWR MLOCA and PWR LLOCA. Also, use of the NUREG-1829 estimate rather than the Bayesian update result for PWR SLOCA results in approximately a 150% increase in the mean. However, the NUREG-1829 mean lies within the 95% of the Bayesian update distribution.

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

Plant Type	LOCA Category	Break Size Range (equivalent diameter, in.)	Gamma Distribution						
			α	β (rcry)	5% (1/rcry)	50% (1/rcry)	Mean (1/rcry)	95% (1/rcry)	Source
BWR	SLOCA	0.5 to 2.0 in.	0.473	7.869E+02	1.75E-06	2.60E-04	6.01E-04	2.36E-03	NUREG-1829
BWR	MLOCA	2.0 to 6.0 in.	0.416	3.767E+03	1.48E-07	4.19E-05	1.10E-04	4.53E-04	NUREG-1829
BWR	LLOCA	> 6.0 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	5.085E+02	5.67E-07	2.58E-04	7.51E-04	3.17E-03	Bayesian Update (note a)
PWR	MLOCA	2.0 to 6.0 in.	0.303	2.312E+03	1.54E-08	3.25E-05	1.31E-04	5.98E-04	Bayesian Update (note a)
PWR	LLOCA	> 6.0 in.	0.295	1.091E+05	2.48E-10	6.41E-07	2.70E-06	1.24E-05	NUREG-1829

a. Bayesian update with NUREG-1829 distribution as prior and 2003 - 2007 as evidence (0 events, 313.3 rcry). For plant-specific analyses where PWSCC is a concern, the NUREG-1829 distributions for PWR SLOCA and MLOCA (Table V) should be used instead of the SPAR suggested distribution.

5 COMPARISON WITH PREVIOUS RESULTS

The suggested LOCA frequencies for the SPAR models presented in this report 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 VII.

Comparing the suggested results with those in NUREG/CR-6928, the suggested results are similar for most of the initiating events. However, results differ for the PWR MLOCA. For the PWR MLOCA, the suggested mean frequency dropped to 1.52E-4/rcry from 5.10E-4/rcry. This decrease is due to a change in method in the use of data from NUREG-1829 and changes in NUREG-1829 table values as that document was finalized. In NUREG/CR-6928, no interpolation was used for LOCA break size splits not explicitly presented in the NUREG-1829 tables. The table entry closest to the break size of concern was used. However, the suggested results used interpolation between NUREG-1829 table entries. Interpolation provides a more precise estimate and also allows for more refined plant-specific calculations if desired.

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

Reactor Type	Initiating Event	Mean Frequency (1/rcry)		
		This Report (Suggested)	NUREG/CR-6928	NUREG/CR-5750
BWR	SLOCA	6.01E-04	5.00E-04	5.0E-04
	MLOCA	1.10E-04	1.04E-04	4.0E-05
	LLOCA	1.07E-05	6.78E-06	3.0E-05
PWR	SLOCA	7.51E-04	5.77E-04	5.0E-04
	MLOCA	1.31E-04	5.10E-04	4.0E-05
	LLOCA	2.70E-06	1.33E-06	5.0E-06

Comparing the suggested results with those in NUREG/CR-5750 indicates changes in both directions. SLOCA results are similar. The suggested MLOCA frequencies are significantly higher. Suggested LLOCA frequencies are lower.

6 CONCLUSIONS

New SLOCA, MLOCA, and LLOCA frequency distributions have been generated for the SPAR models. These new distributions were derived from information in the recently published NUREG-1829 final report. A Bayesian update process was used to modify the NUREG-1829 estimates for PWR SLOCA and MLOCA, based on recent historical evidence. Representative LOCA break size ranges were identified for the SPAR BWR and PWR models. For certain plant-specific analyses, alternative break size ranges may be required. The process outlined in this paper can be used to generate plant-specific LOCA frequencies if plant-specific break size ranges are identified. Also, for plant-specific analyses where PWSCC is a concern, the NUREG-1829 distribution for PWR SLOCA should be used instead of the SPAR suggested distribution.

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