Development of an Integrated Industry Initiating Event Indicator

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ABSTRACT

This report presents the preliminary details and demonstrates the feasibility of an integrated industry initiating event indicator (IIIEI). This indicator could potentially be used in the Industry Trends Program for monitoring industry performance with respect to initiating events. The indicator is related to internal event core damage frequency (CDF), or changes in core damage frequency (ΔCDF), and it allows integrated trending of frequent and infrequent events with different risk (Birnbaum importance measures). The IIIEI combines operating experience for approximately 10 risk significant initiating events with associated CDF-based importance information. The measure proposed is the average per plant of the sum of products of current operating experience for each initiating event with the appropriate risk weight obtained from probabilistic risk assessments (PRAs). Boiling water reactors (BWRs) and pressurized water reactors (PWRs) have different core damage frequencies, which depend to some extent on different initiating events. Also, the risk weights for various initiating events are different for the two types of reactors. Therefore, IIIEI results are presented for each reactor type. Simulations of the predicted IIIEI future performance were performed to establish 95^{th} and 99^{th} percentiles, which will be used as input to the development of thresholds. Actual threshold levels will be determined by an expert panel.

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EXECUTIVE SUMMARY

The purpose of this report is to present preliminary information about an integrated industry initiating event indicator (IIIEI) that is related to risk and to provide information to help establish thresholds for selected performance indicators for the nuclear industry. The information given here should be regarded as preliminary. This report gives a first test of the method; refinements should be expected.

The Industry Trends Program (ITP), discussed in SECY-01-0111, "Development of an Industry Trends Program for Operating Power Reactors," and SECY-02-0058, "Results of the Industry Trends Program for Operating Power Reactors and Status of Ongoing Development," was started to complement the Reactor Oversight Process (ROP) by monitoring and assessing industry-level safety performance. The ITP has the following objectives:

- Collect and monitor industry-wide data that can be used to assess whether the nuclear industry is maintaining the safety performance of operating plants and to provide feedback for the ROP. Results from the ITP are industry-level indicators and not plant-specific indicators, which are covered under the existing ROP.

- Assess the safety significance and causes of any statistically significant adverse industry trends, determine if they represent an actual degradation in overall industry safety performance, and respond appropriately to any safety issues that may be identified.

- Communicate industry-level information to Congress and other stakeholders in an effective and timely manner.

The ROP uses thresholds for its performance indicators to characterize plant-specific performance as green, white, yellow, or red. A related action matrix indicates actions to be taken for single and multiple non-green indications at a plant. In contrast, the ITP is evaluating industry-wide performance. Two different types of industry trend thresholds are envisioned. One is an early indication type of threshold, called an **early-warning threshold**, for use by the NRC to flag degrading performance indicators before the degradations become risk and/or safety significant. This early-warning threshold is based on the detection of a degradation in a performance indicator that is outside the expected industry performance. Early-warning thresholds are expected to be developed primarily based on statistical analyses of industry performance. Trending and early-warning threshold work are presented in a separate report, *Industry Trends Program Status Report* (Eide, Atwood, and Rasmuson 2003). The other type of industry trend threshold, called an **action threshold**, will be used to measure industry performance similar to thresholds used in the ROP process. The present report addresses the development of a risk informed performance indicator and associated information to be used to help establish related action thresholds.

The information for the IIIEI is collected on a plant-specific level. From the plant-specific information, the industry-level initiating event frequencies and trends are estimated for the separate risk significant initiating events. These industry-level frequencies are used to calculate the value of the IIIEI. Thus, a hierarchical structure exists for the information and results (i.e., plant-level, individual industry-level, and integrated).

The hierarchical structure is also present in the use of the IIIEI. At the top level is the IIIEI with its supporting plots and tables. If an increase in the IIIEI occurs, then the individual industry initiating event trends and plots can be used to identify the potential cause of the increase. If more information is needed, then the individual plants and event data are available for further analysis.

Figure ES-1 presents an initial flowchart for conceptual use of the thresholds with the trends. Although seven cornerstones of safety are indicated in the figure, work discussed in this report covers only the initiating events cornerstone. Also, as presently envisioned, risk-significant initiating events will be trended individually and compared against early warning thresholds. The IIIEI integrates the core damage frequency (CDF) impacts of these risk-significant initiating events into a single risk measure that can be compared against action thresholds. The present report defines and characterizes the anticipated performance of the IIIEI, but does not actually develop action thresholds. That effort will be left to an expert panel.

The initiating event study, NUREG/CR-5750, provides data for a large number of initiating event types. A subset of these types has been identified as being risk significant in NUREG-1753. The list of initiating events considered is presented in Table ES-1.

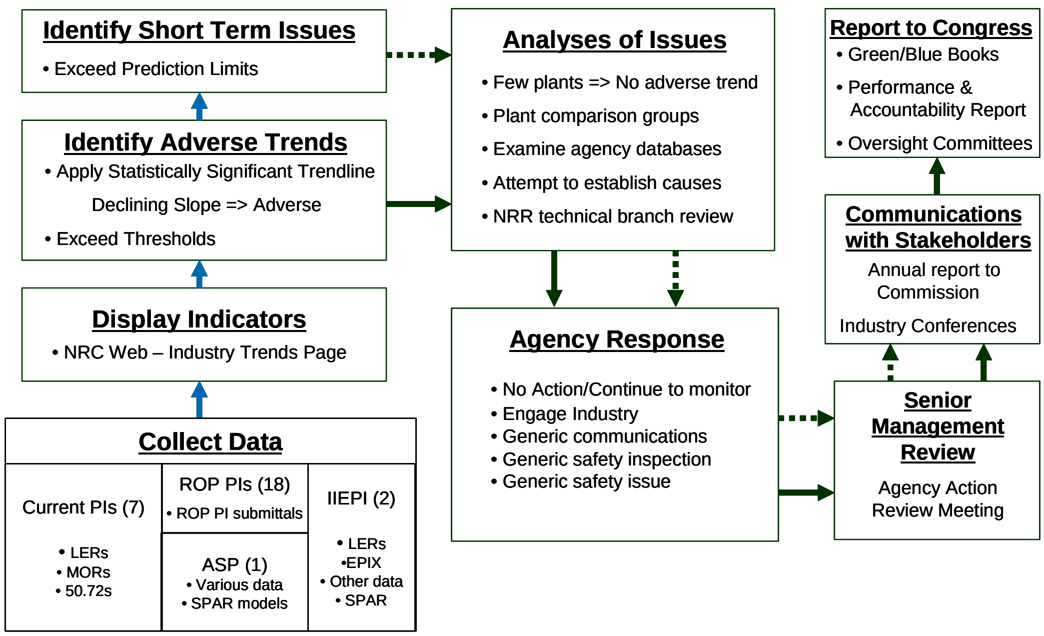

Figure ES-1 Industry Trends Program process flowchart

Core damage frequency for a specific plant can be expressed by the following equation:

$$CDF = \sum_{i=1}^{m} B_i \lambda_i \qquad \text{(ES-1)}$$

where B_i is the partial derivative of CDF with respect to initiating event frequency λ_i. Note that Equation ES-1 is exact if the λ_i's cover all of the initiating events in the PRA. The partial derivative B_i is called the Birnbaum importance measure.

Table ES-1 Baseline Performance for Risk Significant Initiating Events

Risk Significant Initiating Event	Baseline Period Starting Year	Baseline Period Reactor Critical-Years	Baseline Period Number of Events	Baseline Period Mean Frequency (per reactor critical year)
BWR Loss of Instrument Air	1994	231.5	2	0.0108
PWR Loss of Instrument Air	1990	696.1	8	0.0122
Loss of Vital AC Bus	1988	1182.3	32	0.0275
Loss of Vital DC Bus	1988	1182.3	3	0.0030
Loss of Offsite Power	1997	439.4	5	0.0125
Small LOCA	1988	1182.3	5	0.0047
PWR Steam Generator Tube Rupture	1988	800.6	3	0.0044
BWR General Transients	1997	146.9	131	0.895
PWR General Transients	1998	239.0	182	0.764
Loss of Feedwater	1993	785.4	80	0.102
BWR Loss of Heat Sink	1996	176.2	33	0.190
PWR Loss of Heat Sink	1991	641.9	62	0.0974
BWR Stuck Open SRV	1993	258.2	5	0.0213
PWR Stuck Open SRV	1988	800.6	2	0.0031

The IIIEI is defined similarly, but with industry-average values. Also, current values for risk significant initiating events are subtracted from industry-average baseline values, such that the IIIEI risk measure is ΔCDF:

$$IIIEI(\Delta CDF) = \sum_{i=1}^{m} \overline{B}_i (\lambda_i^* - \lambda_{i,baseline}) \qquad \text{(ES-2)}$$

The IIIEI can also be expressed in terms of CDF, rather than ΔCDF, by setting the $\lambda_{i,baseline}$ terms to zero.

For each initiating event considered in Equation ES-2, a baseline period must be established. The baseline period is used to determine a baseline value for the initiating event. Also, the baseline period data are then used as input to the predictive limits analysis. Baseline performance results for the risk significant initiating events are summarized in Table ES-1.

The current estimated frequency λ_i^* is calculated using the information in the current period, i.e., the number of occurrences of the initiating event and the reactor-critical-years. The current period is defined as the most recent *three years*. This choice is made because some of the initiating events are infrequent, and use of three years gives greater stability to the indicator. This approach balances stability and volatility in a manner analogous to the treatment in NUREG-1753.

The Birnbaum importance measure for a given initiating event category, multiplied by that event's current frequency, is an estimate of the CDF contribution from the initiating event current frequency. If the Birnbaum importance measure is for a single plant, then the result is the estimated CDF contribution from that initiator for that plant. If the Birnbaum importance measure is the summation of the Birnbaum importance measures over all plants, then the result is the estimated CDF contribution for the industry (from the initiating event in question). Dividing this summation by the number of plants results in an average Birnbaum per plant. Resulting industry-average Birnbaum importances obtained from the SPAR models are presented in Table ES-2.

Given the industry-average Birnbaum importance measures listed in Table ES-2 and historical industry initiating event data, the IIIEI can be calculated for past years. Results for the fiscal years (FYs) 1997 through 2001 are presented in Figures ES-2 and ES-3 in terms of CDF for BWRs and PWRs, respectively.

To help characterize the expected performance of the IIIEI, what is desired is a predictive distribution for the IIIEI. This could be constructed using historical performance of the IIIEI (as presented in Figures ES-2 and ES-3) or could be established using simulation. However, relevant historical performance of the IIIEI is limited because of the following. Baseline periods for the individual initiating events range from long (FY 1988 through FY 2001) to short (FY 1988 through FY 2001). For the initiating events with short baseline periods, industry performance prior to the baseline period was typically much worse (more events occurring per year) than during the baseline period. Therefore, looking at historical performance of the IIIEI is meaningful only for the period during which all of the initiating events reflect their baseline performance. Because three years of data are used to calculate the IIIEI, this leaves only FY 2000 and FY2001 as appropriate historical values. Therefore, simulation must be used.

Table ES-2 Initiating Event Birnbaum Importance Measures

Initiating Event	Birnbaum Importance Per Plant	
	BWRs	PWRs
Loss of Instrument Air	8.20E-6	8.35E-5
Loss of Vital AC Bus	Not available [a]	Not available [a]
Loss of Vital DC Bus	2.70E-4	2.99E-3
Loss of Offsite Power	3.22E-4	3.25E-4
Small LOCA	5.62E-5	2.52E-3
Steam Generator Tube Rupture	Not applicable	7.89E-4
General Transients	1.36E-6	2.02E-6
Loss of Feedwater	1.45E-5	1.89E-5
Loss of Heat Sink	8.44E-6	1.89E-5
Stuck Open SRV	4.71E-5	6.36E-4

a. None of the SPAR models reviewed included this initiating event.

The predictive distribution for IIIEI was evaluated by simulation. That is, for each kind of initiating event, simulate many values of X_{new} from its predictive distribution. Calculate the resulting values of IIIEI, and observe the resulting mean, variance, and percentiles. The histograms below are obtained in this way, simulating 200,000 values of IIIEI for each graph. This is a large enough sample so that the 50th, 95th, and 99th percentiles are all accurate to about two significant digits.

Figure ES-4 contains the simulated distribution for the BWR IIIEI (CDF). The mean of the distribution is 1.05×10^{-5}/reactor critical year. The 95^{th} percentile of this distribution is 1.63×10^{-5}/reactor critical year, and the 99^{th} percentile is 1.97×10^{-5}/reactor critical year. To convert these results to an equivalent BWR IIIEI (ΔCDF) format, just subtract the baseline mean. Therefore, the 95^{th} percentile for ΔCDF is 5.8×10^{-6}/reactor critical year, while the 99^{th} percentile is 9.2×10^{-6}/reactor critical year.

Figure ES-5 contains the simulated distribution of the PWR IIIEI (CDF). The mean of the distribution is 3.64×10^{-5}/reactor critical year. The 95^{th} and 99^{th} percentiles of this distribution are 5.79×10^{-5}/reactor critical year and 7.05×10^{-5}/reactor critical year. To convert these results to an equivalent PWR IIIEI (ΔCDF) format, just subtract the baseline mean. Therefore, the 95^{th} percentile for ΔCDF is 2.2×10^{-5}/reactor critical year, while the 99^{th} percentile is 3.4×10^{-5}/reactor critical year.

Action thresholds need to be established for the two IIIEIs. In SECY-01-0111, the staff informed the Commission that it was working on an approach to be used in the future that would establish risk-informed thresholds, to the extent practicable, that would be used to assess any indicator trends and to determine an appropriate agency response. Such an approach is viewed as being more objective and predictable than the current approach. In the SRM related to SECY-01-0111, the Commission directed the staff to develop risk-informed thresholds for the industry-level indicators “as soon as practicable.”

The Commission has indicated that the NRC safety goal can be applied on an individual plant basis and that a core damage frequency of 1×10^{-4}/reactor year can be used as a subsidiary goal. The Commission has also emphasized that the safety goals are goals, not limits. In addition, Regulatory Guide 1.174 provides goals for changes in core damage frequency for requested changes in the licensing basis.

It is proposed that the establishment of action thresholds for the two IIIEIs be established by considering the following information:

- Uncertainty in the IIIEIs and the 95% and 99% percentiles results from simulations
- Distributions of the Birnbaum importance measures and understanding of the groups of plants that have large values for specific initiating events
- Major contributors to the IIIEIs
- Sensitivity of IIIEIs to initiating events, especially those with lower frequencies
- Other factors, such as the NRC safety goal policy and Regulatory Guide 1.174.

An expert panel would be established to propose threshold values that satisfy policy and operational needs and objectives.

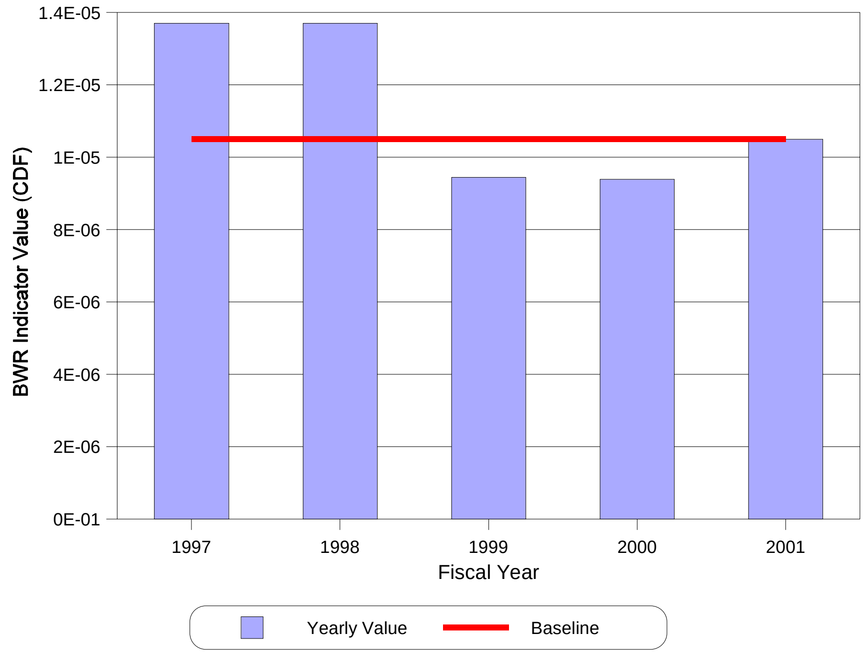

Figure ES-2 BWR integrated industry initiating event results (CDF)

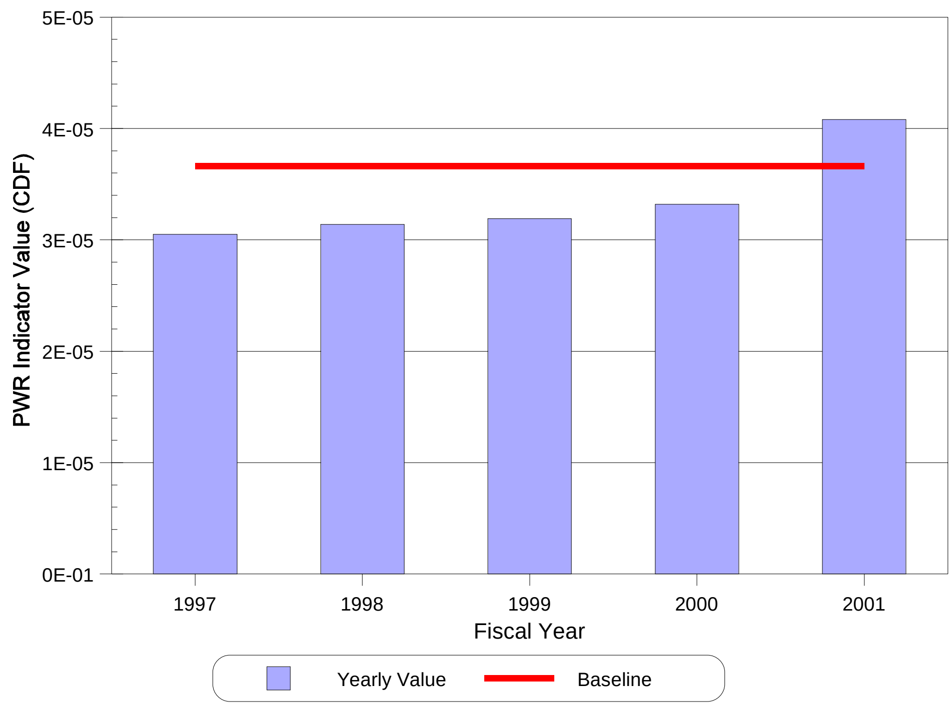

Figure ES-3 PWR integrated industry initiating event indicator results (CDF)

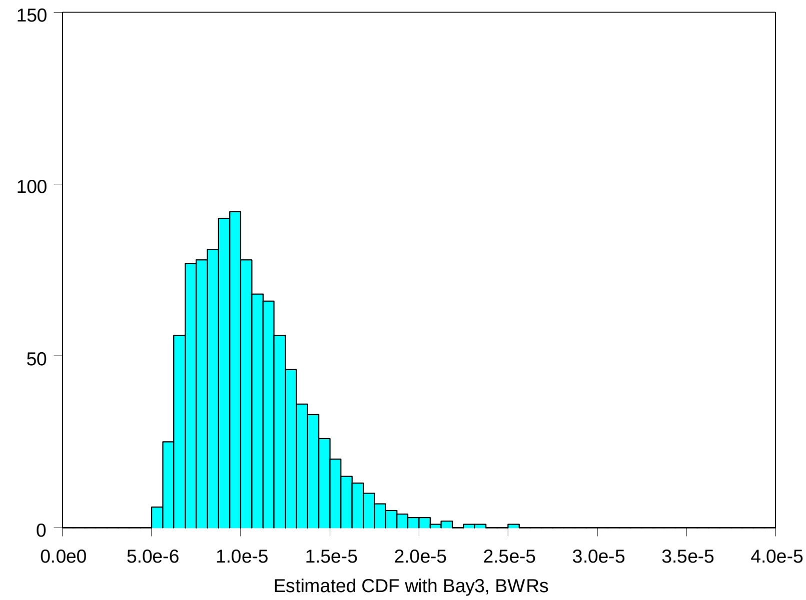

Figure ES-4 Predictive distribution of IIIEI (CDF) for BWRs

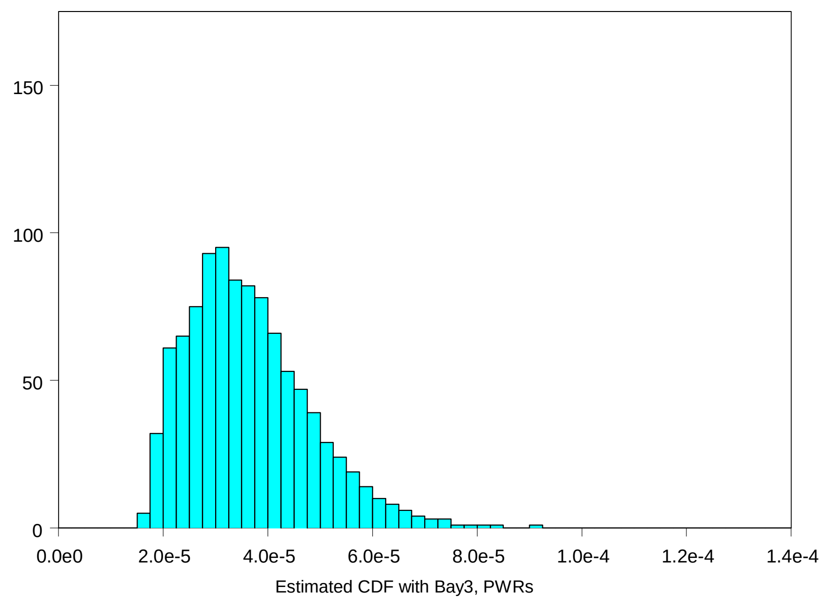

Figure ES-5 Predictive distribution of IIIEI (CDF) for PWRs

1. INTRODUCTION

1.1 Purpose and Relation to Other Work

The purpose of this report is to present preliminary information about an integrated industry initiating event indicator (IIIEI) that is related to risk and to provide information to help establish thresholds for selected performance indicators for the nuclear industry. The information given here should be regarded as preliminary. This report gives a first test of the method; refinements should be expected.

The current work builds on the plant-specific work of Hamzehee et al. (2002) and the work being done for the mitigating systems performance index pilot program. In particular, the present work uses internal event core damage frequency (CDF or ΔCDF), as a measure of risk, drawing from Hamzehee et al. However, this effort is focused on industry performance, not plant-specific performance. The risk-significant initiating events used follow Poloski et al. (1999) and are identified in Hamzehee et al.

The Nuclear Regulatory Commission (NRC) provides oversight of plant safety performance on a plant-specific basis using both inspection findings and plant-level performance as part of its Reactor Oversight Process (ROP). Annually, the NRC prepares the *Performance and Accountability Report*, NUREG-1542 (NRC 2002a), on a fiscal year basis for submittal to Congress. In that report under the Nuclear Reactor Safety Program section, a performance goal is "Maintain safety, protection of the environment, and the common defense and security." This performance goal has five performance measures. The first performance measure is "No statistically significant adverse industry trends in safety performance."

The Industry Trends Program (ITP), discussed in SECY-01-0111, "Development of an Industry Trends Program for Operating Power Reactors" (NRC 2001), and SECY-02-0058, "Results of the Industry Trends Program for Operating Power Reactors and Status of Ongoing Development" (NRC 2002b), was started to complement the ROP by monitoring and assessing industry-level safety performance. The ITP has the following objectives:

9. Collect and monitor industry-wide data that can be used to assess whether the nuclear industry is maintaining the safety performance of operating plants and to provide feedback for the ROP. Results from the ITP are industry-level indicators and not plant-specific indicators, which are covered under the existing ROP.

10. Assess the safety significance and causes of any statistically significant adverse industry trends, determine if they represent an actual degradation in overall industry safety performance, and respond appropriately to any safety issues that may be identified.

11. Communicate industry-level information to Congress and other stakeholders in an effective and timely manner.

The specific purposes of the ITP are (1) to provide assurance that the nuclear industry is maintaining the safety performance of operating reactors and (2) to enhance stakeholder confidence in the efficacy of the NRC's processes.

The ITP clearly addresses the first performance measure listed above – no statistically significant adverse industry trends in safety performance. Also, a focus of the ITP is to assess the safety significance of statistically significant adverse industry trends. Currently, the ITP is focusing on trends of industry-level indicators originally developed by the former Office for Analysis and Evaluation of Operational Data (AEOD) and trends of Accident Sequence Precursor (ASP) events. Ongoing ITP development work is described below:

> The staff is continuing to use the AEOD and ASP indicators while it develops additional indicators that are more risk-informed and better aligned with the cornerstones of safety in the Reactor Oversight Process (ROP). These additional indicators will be developed in phases and qualified for use in the ITP and the annual report to Congress. In addition, the staff is developing risk-informed thresholds for the appropriate indicators, which will be used to establish a predictable agency response based on safety significance. (NRC 2002b)

These additional industry indicators should have the following characteristics:

- They can be used as performance measures in the NRC's performance and accountability report to Congress.
- They are complementary to the plant-specific ROP.
- They provide industry information for an ROP cornerstone (initiating events).
- They use industry data available from current NRC programs.
- They are related to or tied closely to risk (CDF or ΔCDF).
- Risk-informed methods are used to assess their significance [e.g., a safety goal, Regulatory Guide 1.174 (NRC 2002c)].

With respect to the last bullet, the Commission has indicated that the NRC safety goal can be applied on an individual plant basis and that a CDF of 1×10^{-4} per reactor year can be used as a subsidiary goal. The Commission has also emphasized that the safety goals are goals, not limits. In addition, Regulatory Guide 1.174 provides goals for changes in core damage frequency for requested changes in the licensing basis.

SECY-99-007 (NRC 1999) identifies initiating events as the first ROP cornerstone of safety. Initiating events are related to risk via CDF. An expression that combines risk information and operating experience for initiating events has been developed. This expression is related to CDF and also ΔCDF. Such an expression, or a similar one, is a possible candidate for an integrated industry initiating event indicator (IIIEI) and is presented in this report. Risk-informed thresholds can be established that consider (1) the subsidiary safety goal for CDF and (2) the characteristics and behavior of the integrated indicator.

The trends for the individual initiating events can be estimated, and they can be used as subsidiary industry performance indicators. Thresholds for the individual initiating events can be set to monitor each of these trends. Such thresholds can be viewed as early-warning thresholds. Trending and early-warning threshold work is documented in a separate report (Eide, Atwood, and Rasmuson 2003). However, some of the results are presented in this report for reference purposes.

In SECY-01-0111, the staff informed the Commission that it was working on an approach to be used in the future that would establish risk-informed thresholds, to the extent practicable, that would be used to assess any indicator trends and to determine an appropriate agency response. Such an approach is viewed as being more objective and predictable. In the Staff Requirements Memorandum (SRM) related to SECY-01-0111, the Commission directed the staff to develop risk-informed thresholds for the industry-level indicators "as soon as practicable."

1.2 Outline of This Report

The sections of this report are as follows:

Section 1. Introduction

Section 2. Background

Section 3. Development of the IIIEI

Section 4. Characteristics of the IIIEI

Section 5. Action thresholds for the IIIEI

Section 6. Questions for reviewers

Section 7. Conclusions

Section 8. References

Appendix A. Mathematical details of the IIIEI

Appendix B. Mathematical details of predictive distributions for initiating events

Appendix C. Initiating event trend plots and prediction limits

Appendix D. Initiating event Birnbaum importance measures

Appendix E. IIIEI simulation, uncertainty, and sensitivity results

Appendices B and C are presented mainly for informational purposes. Details of the trending and early-warning threshold work are presented in the report by Eide, Atwood, and Rasmuson (2003).

2. BACKGROUND

The information for the IIIEI is collected on a plant-specific level. From the plant-specific information, the industry-level initiating event frequencies and trends are estimated for the separate risk significant initiating events. These industry-level frequencies are used to calculate the value of the IIIEI. Thus, a hierarchical structure exists for the information and results (i.e., plant-level, individual industry-level, and integrated).

The hierarchical structure is also present in the use of the IIIEI as shown in Figure 1. At the top level is the IIIEI with its supporting plots and tables. If an increase in the IIIEI occurs, then the individual industry initiating event trends and plots can be used to identify the potential cause of the increase. If more information is needed, then the individual plants and event data are available for further analysis.

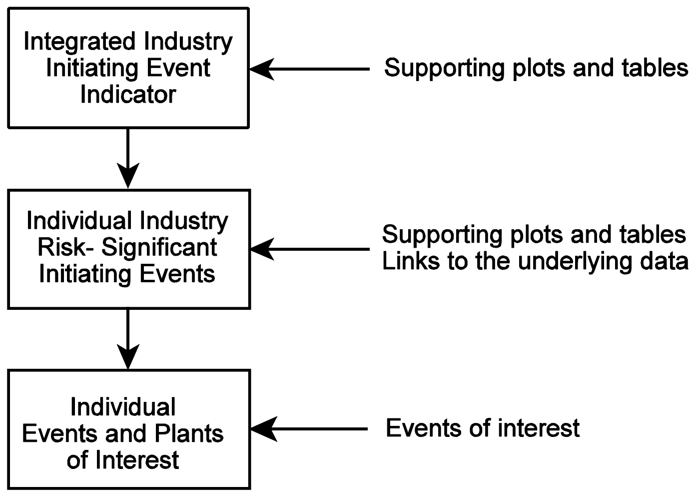

Figure 1 Hierarchical nature of the indicators

The ROP uses thresholds for its performance indicators to characterize plant-specific performance as green, white, yellow, or red. A related action matrix indicates actions to be taken for single and multiple non-green indications at a plant. In contrast, the ITP is evaluating industry-wide performance. Types of thresholds envisioned for the ITP are discussed in this section.

Two different types of industry trend thresholds are envisioned. One is an early indication type of threshold, called an **early-warning threshold**, for use by the NRC to flag degrading performance indicators before the degradations become risk and/or safety significant. This early-warning threshold may be based on the detection of a degradation in a performance indicator that is outside the expected industry performance, or it may be based on a rate of change type of analysis. The other type of industry trend threshold, called an **action threshold**, will be used to measure industry performance similar to thresholds used in the ROP process.

The early-warning thresholds are expected to be developed primarily based on statistical analyses of industry performance. Trending and early-warning threshold work are presented in a separate report (Eide, Atwood, and Rasmuson 2003). The present report addresses the development of a risk informed performance indicator and associated information to be used to help establish related action thresholds.

Action thresholds should be risk informed to the extent practical. Therefore, the development of such thresholds should not be based solely on statistical methods. Instead, a combination of threshold development methods will be used. Inputs from each of the methods will be technically evaluated by an expert panel to obtain the resultant action thresholds.

Figure 2 presents an initial flowchart for conceptual use of the thresholds with the trends. Although seven cornerstones of safety are indicated in the figure, work discussed in this report covers only the initiating events cornerstone. Also, as presently envisioned, risk-significant initiating events will be trended individually and compared against early warning thresholds. The IIIEI integrates the CDF-related impacts of these risk-significant initiating events into a single risk measure that can be compared against action thresholds. The present report defines and characterizes the anticipated performance of the IIIEI, but does not actually develop action thresholds. That effort will be left to an expert panel.

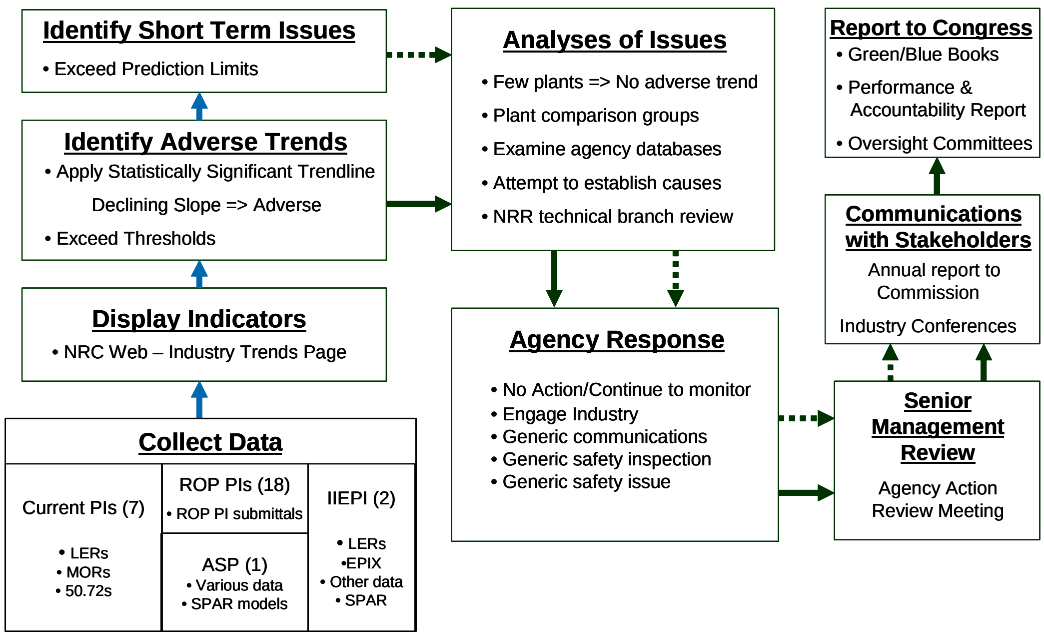

Figure 2 Industry Trends Program process flowchart

3. DEVELOPMENT OF THE IIIEI

3.1 Description

An integrated industry initiating events indicator or IIIEI is proposed. It combines operating experience for approximately 10 risk significant initiating events with associated internal event CDF-based importance information. The measure combines frequent and infrequent events with different risk (Birnbaum importances). The measure proposed is the average per plant of the sum of products of current operating experience for each initiating event with the appropriate risk weight obtained from plant-specific probabilistic risk assessments (PRAs). Boiling water reactors (BWRs) and pressurized water reactors (PWRs) have different core damage frequencies, which depend to some extent on different initiating events. Also, the risk weights for various initiating events are different for the two types of reactors. Therefore, integrated indicator results are presented for each reactor type. Figure 3 presents the concept graphically.

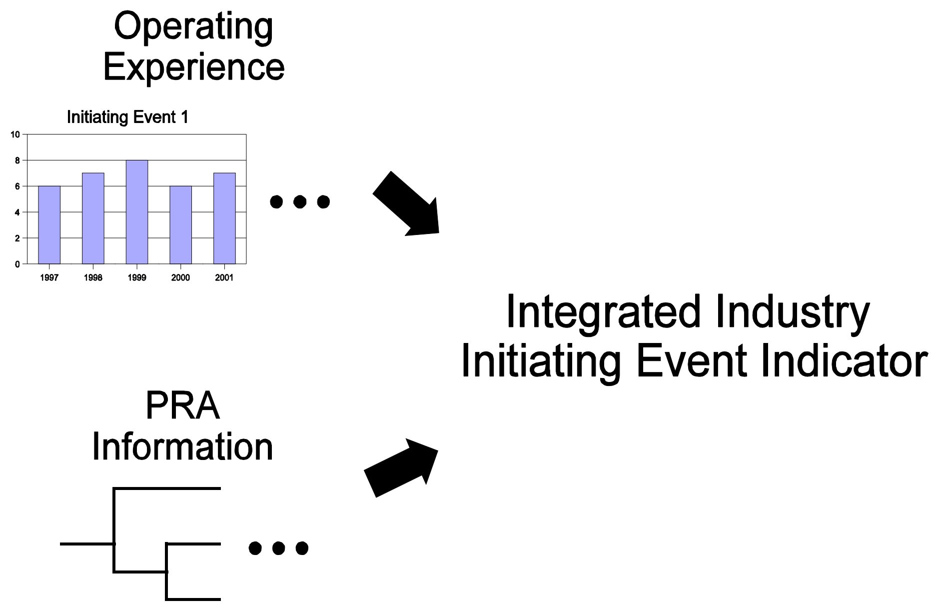

Figure 3 Integrated industry initiating event indicator overview

3.2 List of Initiating Events

The initiating event study, NUREG/CR-5750 (Poloski et al. 1999), provides data for a large number of initiating event types. A subset of these types has been identified as being risk significant in NUREG-1753 (Hamzehee et al. 2002). The list of initiating events considered is presented in Table 1.

There is some overlap in the initiating events listed in Table 1. The General Transients category includes both BWR General Transients and PWR General Transients. Also, the Loss of Heat Sink category includes both BWR and PWR Losses of Heat Sink. If these two categories are eliminated, then there is no overlap among the other categories. BWRs have nine risk-significant initiating events, while PWRs have 10. The five initiating events listed as common to both BWRs and PWRs did not show a significant difference in initiating event frequencies between the two categories of plants. Initiating events divided into BWR and PWR categories have significantly different frequencies.

Table 1 Risk Significant Initiating Events

Loss of Offsite Power Loss of Safety-Related Vital AC Bus Loss of Safety-Related Vital DC Bus Small/Very Small Loss of Coolant Accident General Transients (omitted) Loss of Feedwater Loss of Heat Sink (omitted)
BWR Loss of Instrument Air/Control Air BWR General Transients BWR Stuck Open Safety/Relief Valve BWR Loss of Heat Sink
PWR Loss of Instrument Air/Control Air PWR General Transients PWR Loss of Heat Sink PWR Stuck Open Safety/Relief Valve PWR Steam Generator Tube Rupture

3.3 Mathematical Formulation

Core damage frequency for a specific plant can be expressed by the following equation:

$$CDF = \sum_{i=1}^{m} B_i \lambda_i \qquad (1)$$

where B_i is the partial derivative of CDF with respect to initiating event frequency λ_i. Appendix A contains the mathematical details for this expression. Note that Equation 1 is exact if the λ_i's cover all of the initiating events in the PRA. The partial derivative B_i is called the Birnbaum importance measure.

Four possible ways of calculating an industry-level CDF indicator for initiating events are shown in Table 2. The choices involve the use of plant-specific information or industry-level information.

Table 2 Possible Ways of Estimating the IIIEI

Frequencies	Importance Measures	
	Plant Specific	Industry
Plant Specific	Equation 2	Equation 3
Industry	Equation 4	Equation 5

The four possible equations for the IIIEI are presented below. The notation is also defined. Note that all λ's are estimates of true values.

Notation

$$\lambda_{ui} = \text{Plant-specific frequency for initating event } i \text{ at unit } u$$
$$\lambda_i^* = \text{Industry frequency for initiating event } i$$
$$N = \text{Number of units (plants)}$$
$$m = \text{Number of initiating events}$$
$$\overline{\lambda_i} = \frac{1}{N}\sum_{u=1}^{N} \lambda_{ui} = \text{Arithmetic mean of plant-specific frequencies}$$
$$B_{ui} = \text{Plant-specific importance measure for } i^{\text{th}} \text{ IE at unit } u$$
$$\overline{B_i} = \frac{1}{N}\sum_{i=1}^{N} B_{ui}$$

Plant-specific frequencies and plant-specific importance measures

$$IIIEI = \frac{1}{N}\sum_{u=1}^{N}(\sum_{i=1}^{m} B_{ui}\lambda_{ui}) \tag{2}$$

Plant-specific frequencies and industry-average importance measures

$$IIIEI = \frac{1}{N}\sum_{i=1}^{m}\overline{B_i}\sum_{u=1}^{N}\lambda_{ui} = \sum_{i=1}^{m}\overline{B_i}\,\frac{1}{N}\sum_{u=1}^{N}\lambda_{ui} = \sum_{i=1}^{m}\overline{B_i}\,\overline{\lambda_i} \tag{3}$$

Industry-average frequencies and plant-specific importance measures

$$IIIEI = \frac{1}{N}\sum_{u=1}^{N}\sum_{i=1}^{m} B_{ui}\lambda_i^* = \sum_{i=1}^{m}(\frac{1}{N}\sum_{u=1}^{N} B_{ui})\lambda_i^* = \sum_{i=1}^{m}\overline{B_i}\lambda_i^* \tag{4}$$

Industry-average frequencies and industry-average importance measures

$$IIIEI = \sum_{i=1}^{m}\overline{B_i}\lambda_i^* \tag{5}$$

Note that Equations 4 and 5 are the same. Equation 2 uses plant-specific importance measures and initiating event frequencies, and Equation 3 uses the arithmetic mean of the plant-specific initiating event frequencies. Each industry average frequency in Equations 4 and 5 is based on a model with a single frequency for the entire industry; this differs from assuming distinct plant-specific frequencies and then averaging them. Since the ITP looks at industry trends, Equation 5 will be used to demonstrate the concepts, that is, the sum of the product of the industry average frequency and its corresponding average Birnbaum importance measure.

This report does not investigate the sensitivity of the IIIEI to the various equations listed above. Results are presented only for Equation 5 (or, equivalently, Equation 4). Further development work would be needed to implement Equation 2 or 3. For the risk significant initiating events with low frequencies, few or no events are expected in a year at the industry level. At the plant-specific level, almost all plants would have no events within a year. In such cases, the methodology used to calculate the plant-specific frequencies (in Equations 2 and 3) is especially important.

Equation 5 can also be written as a difference about a point, as shown in Appendix A. This point can be a baseline performance or some other value. The three quantities that are necessary are (1) the baseline performance, if a difference is to be used, (2) the current initiating event frequencies, and (3) the importance measures. Each of these will now be discussed.

3.4 Baseline Performance

For each initiating event considered, a baseline period must be established. The baseline period is used to determine a baseline value for the initiating event. Also, the baseline period data are then used as input to the predictive limits analysis.

The baseline period should have the following desirable characteristics:

- The baseline period is long enough to give a good estimate of the frequency, not strongly influenced by random variation.

- The baseline period is short enough that the true frequency is approximately constant during the entire period.

- The baseline period minimizes the resulting upper prediction limits.

Because of the first bulleted item, it was decided that every baseline period should contain at least four years. For each initiating event, the history was examined back to the earliest year of data, 1988. Candidate baseline periods were considered, starting in any year from the earliest year to 1998 and ending in 2001. (Because of the requirement for at least four years of data, 1998 is the latest starting year allowed, given data through 2001.) For each candidate baseline period, a trend model was fitted to the data, and the p-value for testing the no-trend model was calculated. In this way, each candidate starting year was assigned a corresponding p-value. A p-value > 0.2 was regarded as showing little evidence of a trend during the period. The baseline period was selected to balance the competing criteria shown with the above bullets. Both the visual plot and the p-values were used in the decision.

The decisions were made by consensus judgment, but in retrospect the chosen baseline periods all satisfied rules 1 - 4 given below.

1. Use at least four years of data.

2. If the trend in the initiating event is downward, then:

    - Do not go back far enough to make the initiating event appear non-constant (i.e. with p-value < 0.2). Thus, if the starting year is 1997 or earlier, all the p-values for years from the starting year through 1997 should be > 0.2.

    - In addition, if (p-value for year i) – (p-value for year i–1) > 0.4, do not include year i–1. Start with year i.

3. If, instead, the pattern for the initiating event is U-shaped (downward-low-upward), then:

- Go back as far as possible while achieving an overall appearance of constant indicator (i.e. with overall p-value > 0.2). The starting year is the earliest year for which the p-value is > 0.2. However, after the starting year some p-values may be < 0.2.

- If the U-shaped portion is preceded by other zigzags, apply Rule 3a using only the U-shaped portion.

4. If there are very few events, so upward and downward patterns cannot be identified clearly, use Rule 3.

The combined effect of Rules 2 and 3 is to keep the thresholds fairly low. Rule 2 tends to exclude past high values, and Rule 3 allows past low values. Rule 4, which defaults to Rule 3 in cases of sparse data, allows more years of data than defaulting to Rule 2, although in practice any rule leads to using all the data when there are very few observed events.

Baseline performance results for the risk significant initiating events are summarized in Table 3. The mean frequencies in Table 3 were obtained by updating a Jeffreys prior with the experience from the baseline periods as chosen above. With this prior, the posterior mean frequency = (baseline period number of events + 0.5)/(baseline period reactor-critical-years). Trend plots for the risk significant initiating events are presented in Appendix C. Also shown in the trend plots are associated 95% and 99% prediction limits (potential candidates for early-warning thresholds, as discussed previously). The prediction limit evaluation methodology is explained in Appendix B.

3.5 Current Value

The current estimated frequency λ_i^* is calculated using the information in the current period, i.e., the number of occurrences of the initiating event and the reactor-critical-years. Several different ways exist for calculating the current frequency. One way is to use the maximum likelihood estimator. Another way is to define a prior distribution for the frequency and then update it. Other issues deal with the number of years to use in the calculation of the current frequency – one year, two years, or three years.

The following approach is recommended, based on parametric studies discussed in Appendix E. The current period is defined as the most recent *three years*. This choice is made because some of the initiating events are infrequent, and use of three years gives greater stability to the indicator. This approach balances stability and volatility in a manner analogous to the treatment in NUREG-1753.

The current estimates for initiating event frequencies, λ_i^*, for this demonstration are obtained as follows:

a. Construct the constrained noninformative prior distribution for the initiating event in question using the baseline mean (Table 3). This prior is a gamma(0.5,$1/(2\bar{\lambda}_{i,baseline})$) distribution.

b. For the current period, update this prior with current data to obtain the posterior distribution, which is gamma(x + 0.5, t + $1/(2\bar{\lambda}_{i,baseline})$).

c. The mean of this distribution is the estimate for the current period, namely
$\lambda_i^* = (x + 0.5)/(\, t + 1/(2\bar{\lambda}_{i,baseline}))$.

Table 3 Baseline Performance for Risk Significant Initiating Events

Risk Significant Initiating Event	Baseline Period Starting Year	Baseline Period Reactor Critical-Years	Baseline Period Number of Events	Baseline Period Mean Frequency (per Reactor Critical Year)
BWR Loss of Instrument Air	1994	231.5	2	0.0108
PWR Loss of Instrument Air	1990	696.1	8	0.0122
Loss of Vital AC Bus	1988	1182.3	32	0.0275
Loss of Vital DC Bus	1988	1182.3	3	0.0030
Loss of Offsite Power	1997	439.4	5	0.0125
Small LOCA	1988	1182.3	5	0.0047
PWR Steam Generator Tube Rupture	1988	800.6	3	0.0044
General Transients	1998	358.7	289	0.807
BWR General Transients	1997	146.9	131	0.895
PWR General Transients	1998	239.0	182	0.764
Loss of Feedwater	1993	785.4	80	0.102
Loss of Heat Sink	1995	617.1	78	0.127
BWR Loss of Heat Sink	1996	176.2	33	0.190
PWR Loss of Heat Sink	1991	641.9	62	0.0974
BWR Stuck Open SRV	1993	258.2	5	0.0213
PWR Stuck Open SRV	1988	800.6	2	0.0031

3.6 Risk Information

The Birnbaum importance measure for a given initiating event category, multiplied by the change in that event's frequency (current value minus baseline value), is an estimate of the ΔCDF resulting from the change in the initiating event frequency. If the Birnbaum importance measure is for a single plant, then the result is the estimated ΔCDF for that plant. If the Birnbaum importance measure is the summation of the Birnbaum importance measures over all plants, then the result is the estimated ΔCDF for the industry (from changes in the initiating event in question). Dividing this summation by the number of plants results in an average Birnbaum per plant.

Strictly speaking, the Birnbaum importance measure, as typically quantified in risk assessment software packages, is not applicable to initiating events. The Birnbaum importance measure for a given event in a risk model is typically calculated by requantifying the core damage cut sets by setting the event in question to 1.0 and then to 0.0. The Birnbaum importance measure is then the result using 1.0 minus the result using 0.0. This way of calculating the Birnbaum importance measure make sense for basic events within the cut sets. Such events have probabilities that can range from 0.0 to 1.0. However, initiating events can have frequencies ranging from 0.0 to values greater than 1.0. For initiating events, the equations above should have the Birnbaum importance measure replaced by the conditional core damage probability (CCDP) for the initiating event in question. However, the Standardized Plant Analysis Risk (SPAR) Rev. 3i model Birnbaum importance measures for initiating events are identical to the CCDPs, so either can be used. Resulting industry-average Birnbaum importances obtained from the SPAR models are presented in Table 4. Details of the process used to generate these importances are presented in Appendix D.

Table 4 Initiating Event Birnbaum Importance Measures

Initiating Event	Birnbaum Importance Per Plant	
	BWRs	PWRs
Loss of Instrument Air	8.20E-6	8.35E-5
Loss of Vital AC Bus	Not available [a]	Not available [a]
Loss of Vital DC Bus	2.70E-4	2.99E-3
Loss of Offsite Power	3.22E-4	3.25E-4
Small LOCA	5.62E-5	2.52E-3
Steam Generator Tube Rupture	Not applicable	7.89E-4
General Transients	1.36E-6	2.02E-6
Loss of Feedwater	1.45E-5	1.89E-5
Loss of Heat Sink	8.44E-6	1.89E-5
Stuck Open SRV	4.71E-5	6.36E-4

a. None of the SPAR models reviewed included this initiating event.

3.7 IIIEI Historical Performance

The proposed definition of the IIIEI was given by Equation 5 in Section 3.3. Given the industry-average Birnbaum importance measures listed in Table 4, the methodology for evaluating λ_i^* as discussed in Section 3.5, and historical industry initiating event data, the IIIEI can be calculated for past years. Results for the fiscal years (FYs) 1997 through 2001 are presented in Tables 5 and 6 for BWRs and PWRs, respectively. In those tables, the individual initiating event contributions to the overall IIIEI are presented as ΔCDF contributions, reflecting changes with respect to the baseline frequencies listed in Table 3. However, the overall IIIEI results are presented in both CDF and ΔCDF format. Figures 4 and 5 present the IIIEI (CDF) results for BWRs and PWRs, respectively. The baseline CDFs for the IIIEI shown in Figures 4 and 5 were obtained using Equation 5 with baseline mean frequencies replacing the current frequencies (λ_i^*s). Figures 6 and 7 present the same information in terms of ΔCDF for BWRs and PWRs, respectively. By definition, in these figures the baseline ΔCDF is zero.

The IIIEI results for FY 1997 through FY 2001 are not independent of the data used to establish the baseline mean frequencies. Therefore, in the future as this overlap of data disappears, the variation in the IIIEI results may increase compared to what is presented in Figures 4 through 7.

Table 5 BWR IIIEI Values for FY 1997 through FY 2001

Initiating Event	IIIEI (ΔCDF) Contributions				
	FY 1997	FY 1998	FY 1999	FY 2000	FY 2001
BWR Loss of Instrument Air	-5.74E-08	-5.71E-08	-5.71E-08	3.28E-09	1.38E-10
Loss of Offsite Power	2.97E-06	4.24E-06	-1.27E-06	-1.38E-06	-4.71E-07
Loss of Vital DC Bus	-4.85E-07	-4.79E-07	8.03E-07	7.56E-07	7.15E-07
Loss of Vital AC Bus	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
BWR General Transients	5.88E-07	2.16E-07	5.06E-08	6.59E-08	-3.06E-08
Small Break LOCA	-3.12E-08	-2.68E-08	-1.83E-07	-1.86E-07	-4.21E-08
BWR Loss of Heat Sink	2.75E-07	1.44E-08	2.06E-07	4.91E-07	-5.71E-08
BWR Stuck Open SRV	-3.50E-07	-7.82E-07	-7.82E-07	-7.91E-07	9.18E-09
Loss of Feedwater	3.03E-07	1.24E-07	1.77E-07	-6.35E-08	-1.22E-07
IIIEI Total (ΔCDF)	3.21E-06	3.24E-06	-1.06E-06	-1.11E-06	2.49E-09
IIIEI Total (CDF) [a]	1.37E-05	1.37E-05	9.44E-06	9.39E-06	1.05E-05

• Obtained by adding the IIIEI baseline mean of 1.05E-5/reactor critical year to the ΔCDF results. (See Appendix E for details concerning the baseline mean calculation.)

Table 6 PWR IIIEI Values for FY 1997 through FY 2001

Initiating Event	IIIEI (ΔCDF) Contributions				
	FY 1997	FY 1998	FY 1999	FY 2000	FY 2001
PWR Loss of Instrument Air	-4.61E-08	-2.25E-08	-4.22E-07	-8.28E-07	-4.62E-07
Loss of Offsite Power	3.01E-06	4.28E-06	-1.29E-06	-1.40E-06	-4.77E-07
Steam Generator Tube Rupture	-2.09E-06	-2.06E-06	-2.06E-06	6.10E-07	5.19E-07
Loss of Vital DC Bus	-5.35E-06	-5.29E-06	8.87E-06	8.36E-06	7.91E-06
Loss of Vital AC Bus	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PWR General Transients	9.09E-07	4.81E-07	2.39E-07	1.86E-08	1.64E-08
Small Break LOCA	-1.39E-06	-1.20E-06	-8.28E-06	-8.35E-06	-1.88E-06
PWR Loss of Heat Sink	-3.06E-07	-3.68E-07	-8.06E-07	-4.41E-07	8.72E-09
PWR Stuck Open SRV	-1.03E-06	-1.02E-06	-1.02E-06	-1.04E-06	-1.06E-06
Loss of Feedwater	3.94E-07	1.61E-07	2.29E-07	-8.23E-08	-1.58E-07
IIIEI Total (ΔCDF)	-5.89E-06	-5.04E-06	-4.48E-06	-3.16E-06	4.40E-06
IIIEI Total (CDF) [a]	3.05E-05	3.14E-05	3.19E-05	3.32E-05	4.08E-05

a. Obtained by adding the IIIEI baseline mean of 3.64E-5/reactor critical year to the ΔCDF results. (See Appendix E for details concerning the baseline mean calculation.)

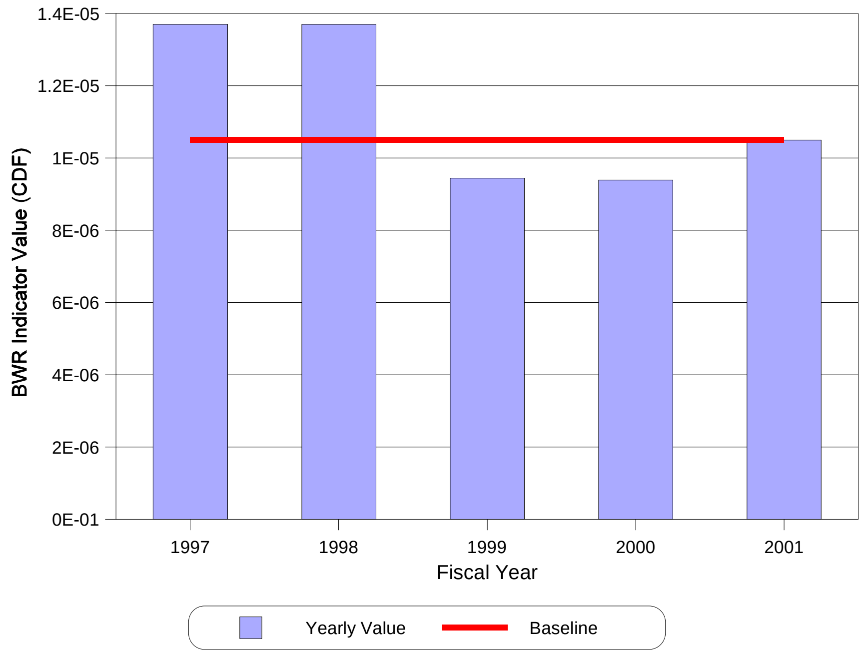

Figure 3 BWR integrated industry initiating event results (CDF)

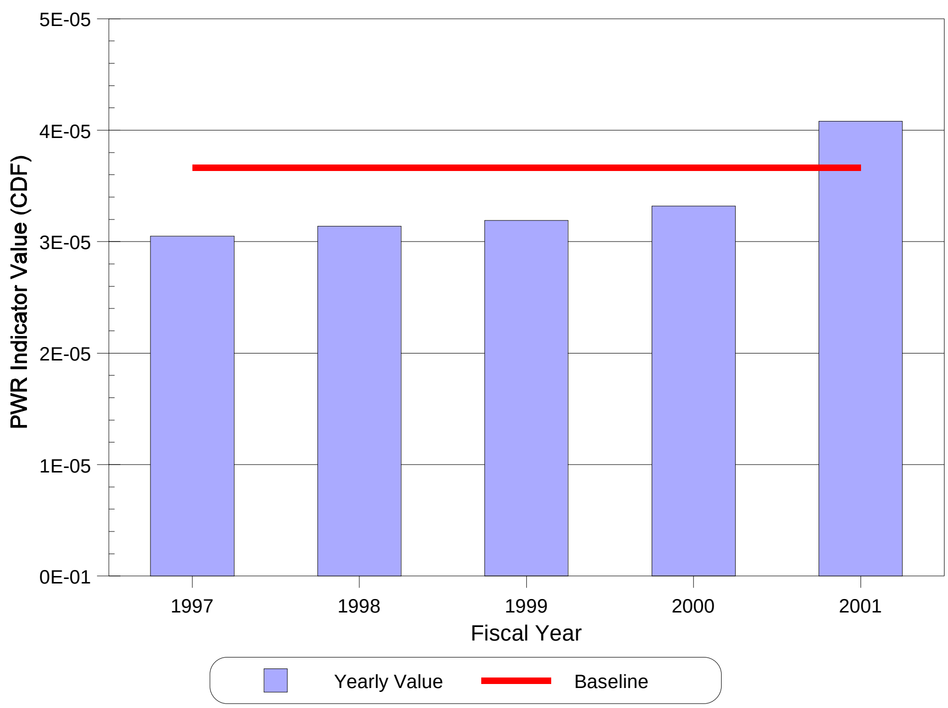

Figure 4 PWR integrated industry initiating event indicator results (CDF)

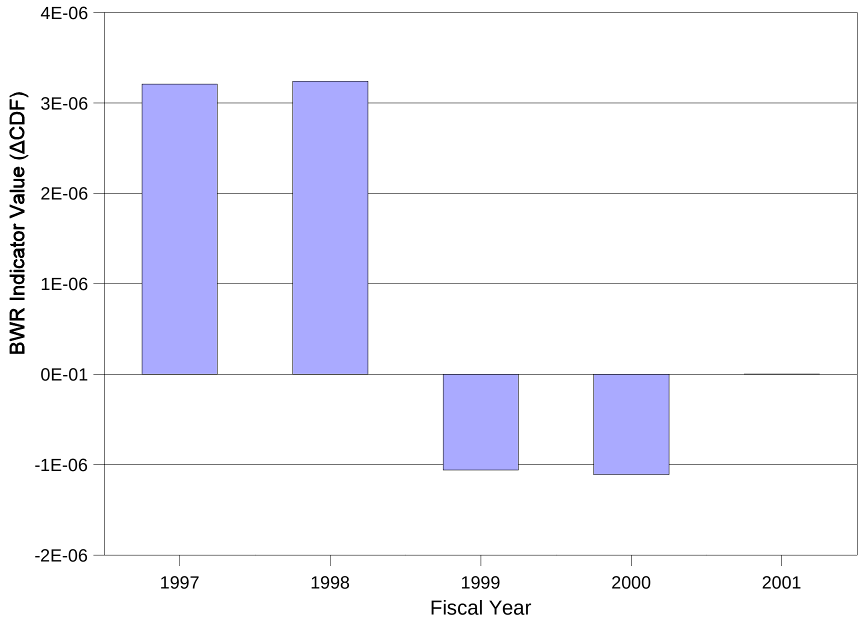

Figure 5 BWR integrated initiating event indicator results (ΔCDF)

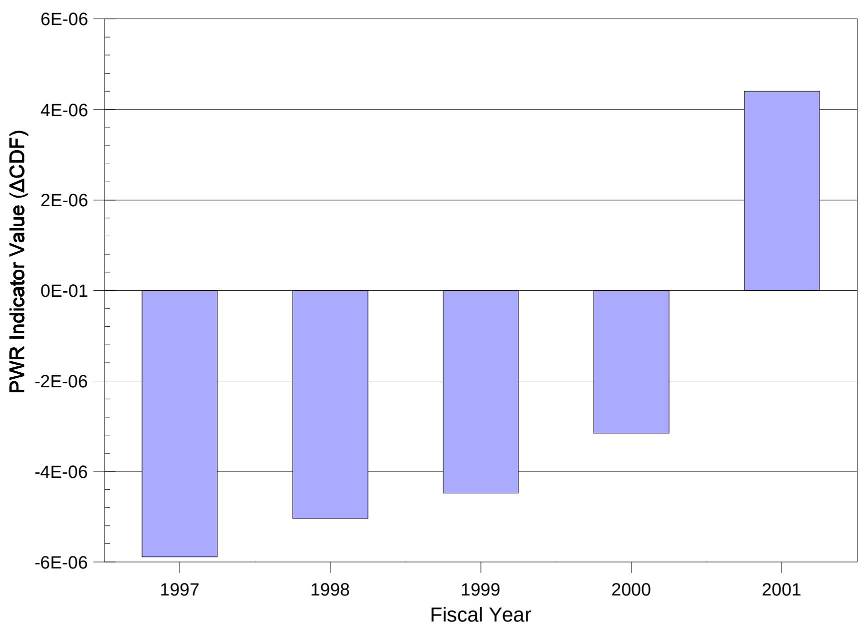

Figure 6 PWR integrated initiating event indicator results (ΔCDF)

4. CHARACTERISTICS OF THE IIIEI

The IIIEI is defined by Equation 5 in Section 3.2:

$$IIIEI(CDF) = \sum_{i=1}^{m} \overline{B}_i \lambda_i^* \tag{6}$$

This is the form of the equation if the IIIEI is evaluated in terms of CDF. If ΔCDF is used, then the equation is the following:

$$IIIEI(\Delta CDF) = \sum_{i=1}^{m} \overline{B}_i (\lambda_i^* - \lambda_{i,baseline}) \tag{7}$$

The characteristics of each of the components in Equations 6 and 7 are discussed in this section. Also, simulation and sensitivity results for the IIIEI are presented.

4.1 Birnbaum Importance Measure Characteristics

The industry average Birnbaum importances in Equations 6 and 7 are defined as the arithmetic averages of the individual plant Birnbaum importances for each initiating event. These industry average Birnbaum importances are treated as constants with no uncertainty. This approach is consistent with the approach used in the ROP pilot program for the mitigating system performance index, which deals with plant-specific performance issues. However, to better understand and judge the proposed approach for quantifying the IIIEI, variation and uncertainty in the Birnbaum importances are discussed in this section.

Individual plant Birnbaum importances can vary widely because of plant-specific designs and other factors. For example, the PWR plant-specific Birnbaum importances for loss of offsite power are summarized in Figure 8. The Birnbaum average is 3.25×10^{-4}, while individual values range from 2.54×10^{-5} to 2.09×10^{-3}. The variation in plant-specific initiating event Birnbaums is summarized in Table 7. The error factors in that table (95th percentile/median) illustrate the variability.

The use of an industry average Birnbaum in Equations 6 and 7 tends to dampen the potential effects on the IIIEI of losses of offsite power occurring at plants with extreme (low or high) Birnbaum importances. For example, if a loss of offsite power occurred at a plant with a very high Birnbaum, then the plant-specific impact on CDF (or ΔCDF) would be high. However, the IIIEI as defined would say that this event could have occurred at any of the plants, and on average the impact on CDF (or ΔCDF) is appropriately modeled by using the industry average Birnbaum for this initiating event. Conversely, if the loss of offsite power occurred at a plant with a very low Birnbaum, then the plant-specific impact on CDF (or ΔCDF) would be low. However, the IIIEI would say that this event could have occurred at other plants with higher Birnbaum importances, and on average the impact is appropriately modeled by using the industry average Birnbaum.

Plant-specific Birnbaum importances obtained from the SPAR models are uncertain because of parameter uncertainty within the models and because of modeling uncertainties (the degree to which the plant model actually reflects plant design and performance). Modeling uncertainties are not addressed in this report. However, Birnbaum uncertainties for a specific plant resulting from parameter uncertainties have been evaluated for several initiating events. The results are summarized in Table 8. The plant-specific Birnbaum uncertainties have a range of error factors from 2.84 to 6.91.

In general, the uncertainty in plant-specific Birnbaum importances (from parameter uncertainties within the SPAR model, Table 8) is lower than the plant-to-plant variability in Birnbaum importances (Table 7).

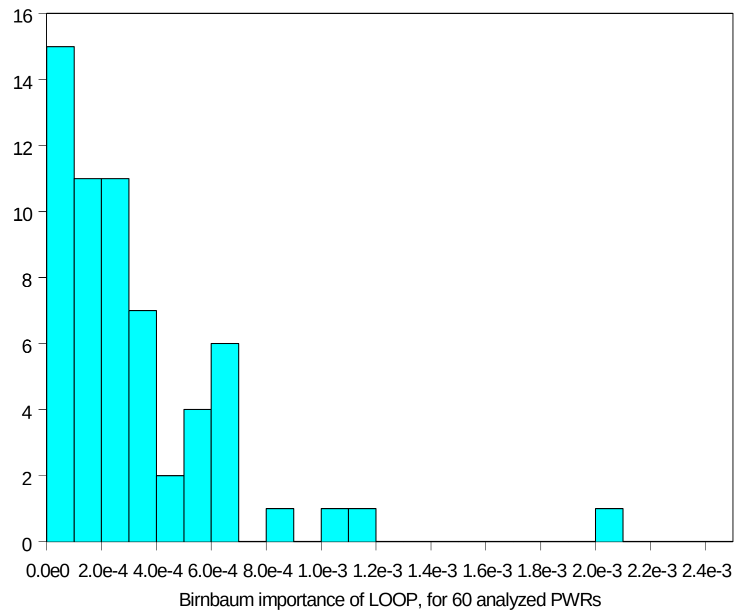

Figure 7 PWR loss of offsite power Birnbaum importance measures

Table 7 Birnbaum Variability Due to Plant-to-Plant Differences in Design and Performance

Initiating Event	Error Factor	
	BWR	PWR
Small LOCA	27.0	4.6
General Transient	23.1	4.3
Loss of Heat Sink	4.9	6.1
Steam Generator Tube Rupture	N.A.	0.6
Loss of Feed Water	4.4	12.3
Loss of Offsite Power	7.2	3.8
Loss of Vital DC Bus	12.6	28.0
Stuck Open Relief Valve	6.0	16.8

Table 8 Birnbaum Uncertainty at a Specific Plant Due to Plant Model Parameter Uncertainties

Initiating Event	5th Percentile	Median	Mean	95th Percentile	Error Factor (95%/median)
Small LOCA	1.89E-4	3.33E-4	4.35E-4	9.45E-4	2.84
Loss of Vital DC Bus	5.52E-3	1.63E-2	2.58E-2	7.32E-2	4.48
Steam Generator Tube Rupture	4.75E-6	5.27E-6	8.56E-6	1.37E-5	2.59
Loss of Offsite Power	2.98E-5	9.83E-5	2.16E-4	6.79E-4	6.91
General Transients [a]	9.09E-7	2.83E-6	4.01E-6	1.06E-5	3.75

a. Includes Loss of Feedwater and Loss of Heat Sink

4.2 Initiating Event Frequency Characteristics

Two types of initiating event frequencies are used in Equations 6 and 7: baseline frequencies ($\lambda_{i,baseline}$'s) and current frequencies (λ_i^*'s). Baseline frequencies were determined from historical data as discussed in Section 3.4. Mean values are presented in Table 3. For the purposes of the IIIEI, these baseline mean frequencies are treated as constants. This implies that the baseline values for IIIEI for BWRs and PWRs (obtained from Equation 6 but with λ_i^* replaced with $\lambda_{i,baseline}$) are also treated as constants.

For BWRs, the baseline IIIEI (CDF) is 1.05×10^{-5}/reactor critical year. Major contributors to the baseline IIIEI are loss of offsite power (38%), loss of heat sink (15%), and loss of feedwater (14%). By definition, the baseline IIIEI (ΔCDF) is zero.

For PWRs, the baseline IIIEI (CDF) is 3.64×10^{-5}/reactor critical year. Major contributors are small LOCA (32%), loss of vital DC bus (24%), and loss of offsite power (11%). More details on the baseline IIIEIs are presented in Appendix E.

Figures 9 and 10 show the Bayesian distributions for the baseline IIIEIs for BWRs and PWRs, respectively, reflecting uncertainties in the baseline frequencies. For BWRs, uncertainty in the loss of offsite power frequency is the largest contributor (85%) to the overall uncertainty. For PWRs, the main contributors to overall uncertainty are uncertainty in the small LOCA frequency (45%) and uncertainty in the loss of DC bus frequency (40%).

Current frequencies (λ_i^*'s) are determined using a Bayesian update process and three years of industry data, as explained in Section 3.5. As industry performance data continue to be collected, the IIIEI will be calculated each fiscal year using data from that fiscal year and the two previous fiscal years. The yearly data will exhibit variability, and the actual IIIEI results will incorporate this variability. As an example, the historical IIIEI results (FY 1997 through FY 2001) presented in Section 3.7 show the BWR IIIEI (CDF) ranging from 9.39×10^{-6} to 1.37×10^{-5}/reactor critical year. (The IIIEI baseline is 1.05×10^{-5}/reactor critical year.) Also, the PWR IIIEI (CDF) ranges from 3.05×10^{-5} to 4.08×10^{-5}/reactor critical year, while the baseline is 3.64×10^{-5}/reactor critical year.

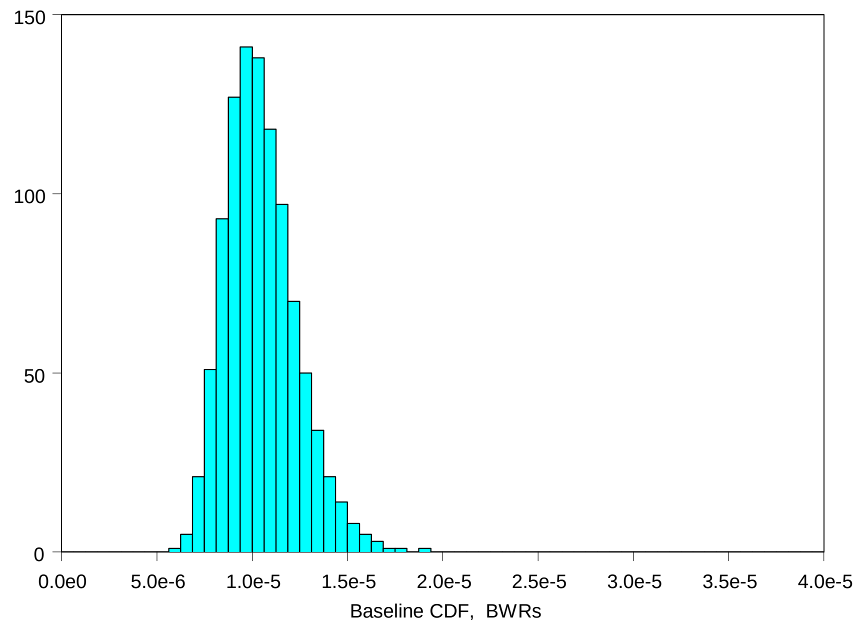

Figure 8 Bayesian distribution of baseline IIIEI (CDF) for BWRs

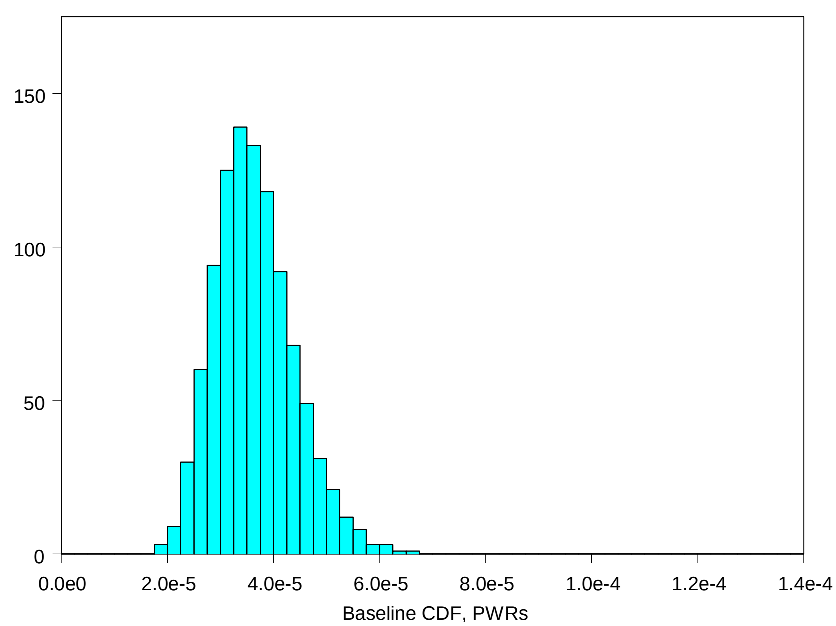

Figure 9 Bayesian distribution of baseline IIIEI (CDF) for PWRs

The Bayesian update process using a constrained noninformative prior affects the variability in the current frequencies. Use of three years of data rather than one tends to dampen the yearly variation. Also, the prior tends to dampen the impact of the industry data. These effects are built into the methodology for determining the current frequencies. Variations in the calculated current frequencies reflect only the yearly variation in the industry data.

4.3 IIIEI Simulation

To help characterize the expected performance of the IIIEI, what is desired is a predictive distribution for the IIIEI. This could be constructed using historical performance of the IIIEI (as presented in Section 3.7) or could be established using simulation. However, relevant historical performance of the IIIEI is limited because of the following. Baseline periods for the individual initiating events range from long (FY 1988 through FY 2001) to short (FY 1988 through FY 2001). For the initiating events with short baseline periods, industry performance prior to the baseline period was typically much worse (more events occurring per year) than during the baseline period. Therefore, looking at historical performance of the IIIEI is meaningful only for the period during which all of the initiating events reflect their baseline performance. Because three years of data are used to calculate the IIIEI, this leaves only FY 2000 and FY2001 as appropriate historical values. Therefore, simulation must be used.

The predictive distribution for IIIEI was evaluated by simulation. That is, for each kind of initiating event, simulate many values of X_{new} from its predictive distribution. Calculate the resulting values of IIIEI, and observe the resulting mean, variance, and percentiles. The histograms below are obtained in this way, simulating 200,000 values of IIIEI for each graph. This is a large enough sample so that the 50th, 95th, and 99th percentiles are all accurate to about two significant digits.

The predictive distribution assumes that the process is unchanged between the baseline period and the current data window. Thus, observed values that are in the extremes of the predictive distribution may be indicative of a change in the process.

Figure 11 contains the simulated distribution for the BWR IIIEI (CDF). (Other simulations using only one year of data and maximum likelihood estimates are presented in Appendix E.) The mean of the distribution is 1.05×10^{-5}/reactor critical year. The 95th percentile of this distribution is 1.63×10^{-5}, and the 99th percentile is 1.97×10^{-5}/reactor critical year. To convert these results to an equivalent BWR IIIEI (ΔCDF) format, just subtract the baseline mean. Therefore, the 95th percentile for ΔCDF is 5.8×10^{-6}/reactor critical year, while the 99th percentile is 9.2×10^{-6}/reactor critical year.

Figure 12 contains the simulated distribution of the PWR IIIEI (CDF). The mean of the distribution is 3.64×10^{-5}/reactor critical year. The 95th and 99th percentiles of this distribution are 5.79×10^{-5} /reactor critical year and 7.05×10^{-5}/reactor critical year. To convert these results to an equivalent PWR IIIEI (ΔCDF) format, just subtract the baseline mean. Therefore, the 95th percentile for ΔCDF is 2.2×10^{-5}/reactor critical year, while the 99th percentile is 3.4×10^{-5}/reactor critical year.

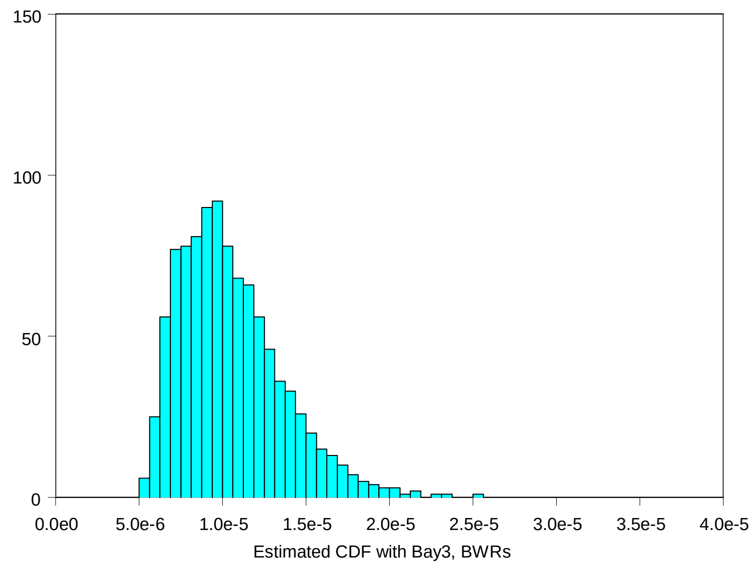

Figure 10 Predictive distribution of IIIEI (CDF) for BWRs

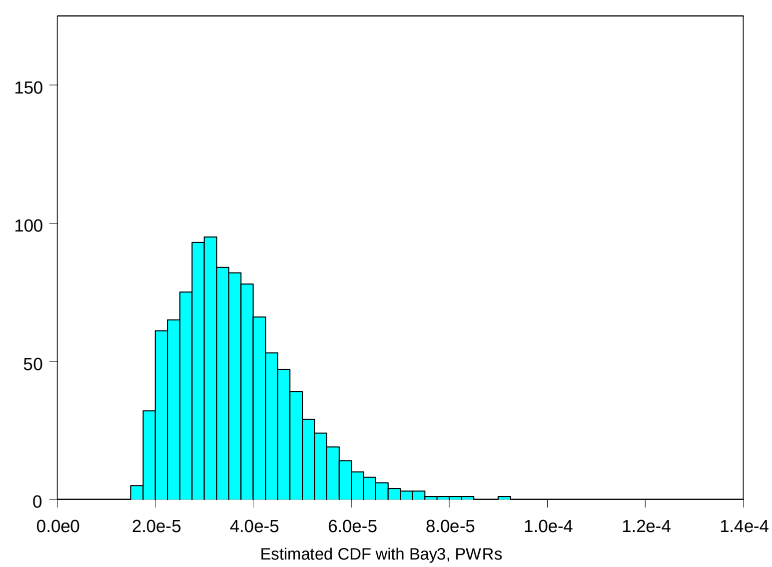

Figure 11 Predictive distribution of IIIEI (CDF) for PWRs

4.4 IIIEI Sensitivity

A sensitivity study was performed to evaluate the impacts on the IIIEI from individual initiating events. For each initiator, the 95% and 99% prediction limits (from Appendix C) were inserted into the IIIEI, while keeping other initiating events at their baseline frequencies. Another sensitivity is to set all the initiating events at their 95% prediction limits and calculate the corresponding IIIEI value. A third is to calculate the IIIEI value when all the initiating event frequencies are set to their 99% prediction limit values. The results of these sensitivity evaluations are presented in Figures 13 and 14 for BWRs and PWRs, respectively. The baseline CDF is also presented in each figure. This information may be useful to an expert panel when they are setting thresholds for the integrated indicator.

For the BWRs, the largest contributor is loss of offsite power. The second and third highest contributors are loss of vital DC bus and stuck open safety relief value. The indicator value is 3.39×10^{-5}/reactor critical year when all initiating events are set at their 95% prediction limits and 4.69×10^{-5}/reactor critical year when they are set at their 99% prediction limits.

For PWRs, the largest contributors are small LOCA and loss of vital DC bus. The indicator value is 2.18×10^{-4}/reactor critical year when all initiators are set at their 95% prediction limits and 3.11×10^{-4}/reactor critical year when they are set at their 99% prediction limits.

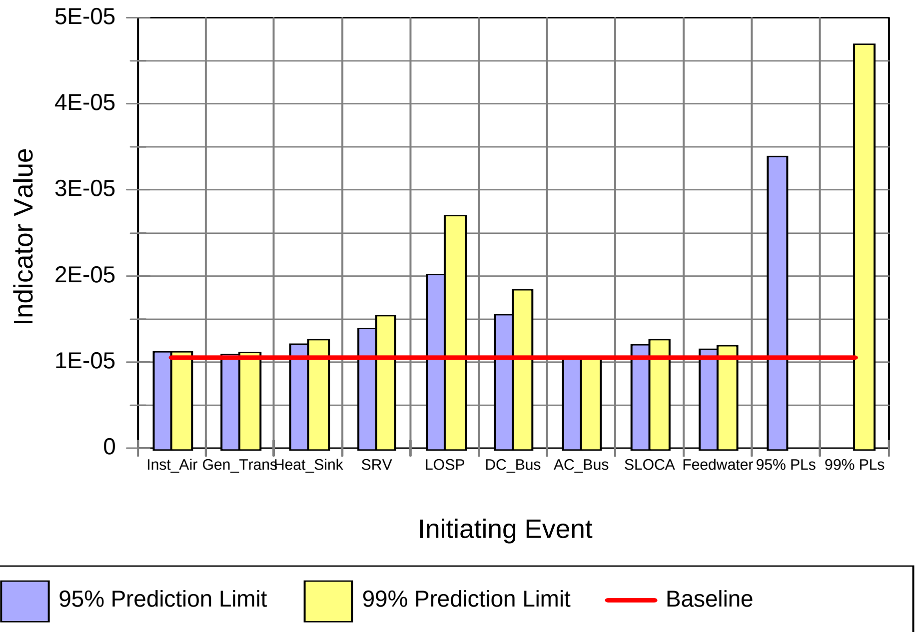

Figure 12 BWR IIIEI (CDF) sensitivity to individual initiating event 95% and 99% prediction limits

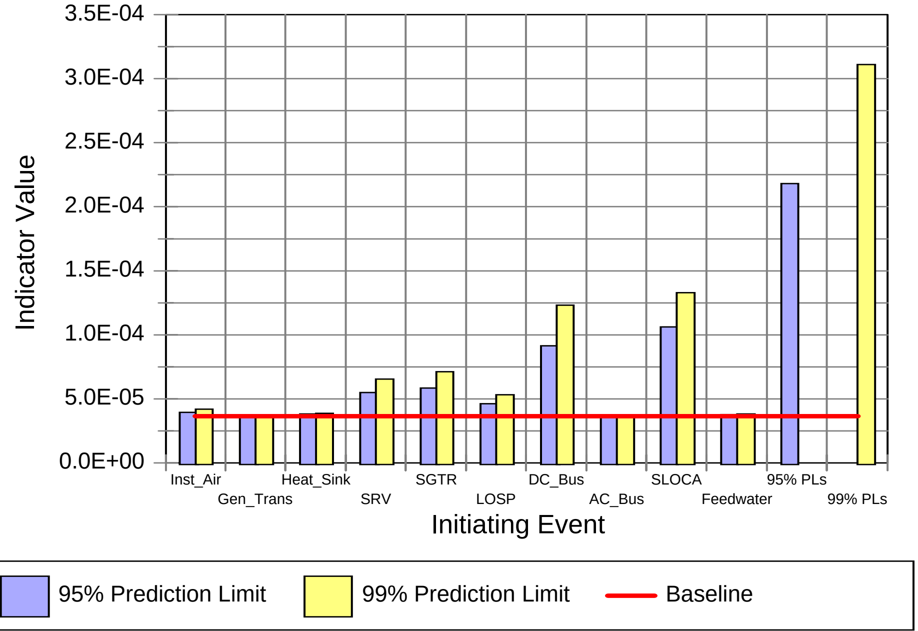

Figure 13 PWR IIIEI (CDF) sensitivity to individual initiating event 95% and 99% prediction limits

5. ACTION THRESHOLDS FOR THE IIIEI

Action thresholds need to be established for the two IIIEIs. In SECY-01-0111, the staff informed the Commission that it was working on an approach to be used in the future that would establish risk-informed thresholds, to the extent practicable, that would be used to assess any indicator trends and to determine an appropriate agency response. Such an approach is viewed as being more objective and predictable than the current approach. In the SRM related to SECY-01-0111, the Commission directed the staff to develop risk-informed thresholds for the industry-level indicators “as soon as practicable.”

The Commission has indicated that the NRC safety goal can be applied on an individual plant basis and that a core damage frequency of 1×10^{-4}/reactor year can be used as a subsidiary goal. The Commission has also emphasized that the safety goals are goals, not limits. In addition, Regulatory Guide 1.174 provides goals for changes in core damage frequency for requested changes in the licensing basis.

It is proposed that the establishment of action thresholds for the two IIIEIs be established considering the following information:

- Uncertainty in the IIIEIs and the 95% and 99% results from simulations
- Distributions of the Birnbaum importance measures and understanding of the groups of plants that have large values for specific initiating events
- Major contributors to the IIIEIs
- Sensitivity of IIIEIs to initiating events, especially those with lower frequencies
- Other factors, such as the NRC safety goal policy and Regulatory Guide 1.174.

An expert panel would be established to propose threshold values that satisfy policy and operational needs and objectives.

6. QUESTIONS FOR REVIEWERS

As this document is reviewed, the following questions/issues should be addressed:

- Is Equation 5 (Section 3.3) rather than Equation 2 or 3 most appropriate for quantifying the IIIEI?

- Is the method for determining baseline performance adequate (Section 3.4).?

- Is the proposed method for calculating current frequencies for the initiating events (Bayes update with three years of data) appropriate (Section 3.5)?

- Should CDF or ΔCDF be used as the measure for the IIIEI (Section 3.7)?

- Given the characteristics of the IIIEI (as discussed in Section 4) and the simulation results, what might be appropriate CDF and ΔCDF action thresholds?

- Should the industry-average Birnbaum importances be obtained from the SPAR models or from industry risk models?

- If the Birnbaum importance measures are obtained from the industry, how will the differences between the two models (industry and SPAR) be addressed?

- How often should initiating event baseline performance be updated?

- How often should the Birnbaum importance measures be updated?

- Is the treatment of uncertainties adequate (Section 4 and Appendix E)?

- Should the thresholds be set so that no one event in a three year period would cause the threshold to be exceeded?

7. CONCLUSIONS

A single industry-wide performance measure that has a logical relationship with risk metrics (CDF) has been presented. This performance measure is potentially relatable to the Safety Goal and allows the rational combination of events with different risk importances and frequencies. The measure is also complementary to plant-specific performance indicators. Finally, the integrated indicator is an estimate of internal event CDF, or equivalently ΔCDF, but the uncertainty in the estimate must be recognized when interpreting the value of the indicator.

8. REFERENCES

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APPENDIX A

Mathematical Details of the IIIEI

MATHEMATICAL DETAILS OF THE IIIEI

The Taylor series for a single variable *x* about a point *a* is given by the following equation:

$$f(x) = f(a) + \sum_{i=1}^{n} \frac{f^{(i)}(a)}{i!}(x-a)^i + \frac{f^{(n+1)}(\xi)}{(n+1)!}(x-a)^{n+1} \tag{A-1}$$

where $f^{(k)}$ is the k^{th} derivatives of the function *f*. If the equation is linear in *x*, the $f^{(1)}$ is constant and the higher-order derivatives are zero, $f^{(k)} = 0$ for $k > 1$. For such cases the Taylor series is exact.

Core damage frequency (CDF) is estimated by the following equation:

$$CDF = \sum_{i=1}^{m} \lambda_i \sum_{j=1}^{n_i} \prod_{k \in S_{ij}} b_k \tag{A-2}$$

where λ_i is the frequency of initiating event *i*, the cut sets are indexed by *j*, and the b_k are basic event probabilities.

The Taylor series expansion of CDF about the baseline value of a is given by

$$f(x) - f(a) = \Delta CDF = f^{(1)}(a)(x-a) \tag{A-3}$$

CDF is a linear equation in any basic event or initiating event. The first derivative is constant, and the higher-order derivatives are zero. That is,

$$f^{(1)}(a) = c,\ f^{(k)}(a) = 0 \text{ for k} > 1 \tag{A-4}$$

The first derivative is called the Birnbaum importance measure

$$f^{(1)}(a) \tag{A-5}$$

The difference is the change in CDF

$$f(x) - f(a) = \Delta CDF = f^{(1)}(a)(x-a) \tag{A-6}$$

If $a = 0$, then the result is equal to CDF, since $f(0) = 0$.

For a multivariate linear equation,

$$f(x_1, \cdots, x_n) = \sum_{i=1}^{n} b_i\, x_i \tag{A-7}$$

the Taylor series is given by

$$f(x_1, \cdots, x_n) = f(a_1, \cdots, a_n) + \sum_{i=1}^{n} \frac{\partial f(x_1, \cdots, x_n)}{\partial x_i}(x_i - a_i) \tag{A-8}$$

where the a_i are the points for expansion.

For initiating events $f(0, \cdots, 0)$ equals 0. Thus, the equation reduces to

$$f(x_1,\cdots,x_n)=\sum_{i=1}^{n}\frac{\partial f(x_1,\cdots,x_n)}{\partial x_i}(x_i-a_i) \tag{A-9}$$

which is exact for this case.

For initiating events equation (A-8) becomes

$$f(\lambda_1,\cdots,\lambda_n)=\sum_{i=1}^{n}\frac{\partial f(\lambda_1,\cdots,\lambda_n)}{\partial \lambda_i}(\lambda_i-\overline{\lambda}_i) \tag{A-10}$$

which is exact. The partial derivative is called the Birnbaum importance measure. It is denoted by B_i. So equation (A-9) can be rewritten as

$$f(\lambda_1,\cdots,\lambda_n)=\sum_{i=1}^{n}B_i(\lambda_i-\overline{\lambda}_i) \tag{A-11}$$

In Equation A-11, $\overline{\lambda}_i$ is equal to 0 for CDF and the baseline frequency for ΔCDF.

APPENDIX B

Mathematical Details of Predictive Distributions for Initiating Events

B.1 PREDICTIVE DISTRIBUTIONS

Predictive distributions for the risk significant initiating events are required for two purposes: establishment of early-warning thresholds (not addressed in this report), and simulation of the IIIEI. This appendix presents the methodology for establishing these predictive distributions.

The early-warning thresholds were established using the predictive distribution of the observable quantity in a future year, given the observed values during a baseline period.

B.1.1 Counts of Events in Time

For events in time (e.g., initiating events, accident sequence precursors) the observable quantity is a count of events. Several predictive distributions can be defined, all having the form of a Poisson-gamma distribution. Note that if all the parameters of the Poisson-gamma distribution are integers, then the Poisson-gamma distribution reduces to the negative binomial distribution. (E.g., see Bernardo and Smith 2000.) The one used in the present work, as discussed in Section E.4 of Appendix E, has probability mass function:

$$\Pr[X = x] = \theta^r \frac{\Gamma(r+x)}{\Gamma(r)\Gamma(x+1)}(1-\theta)^x, \quad x = 0,1,2,\cdots \qquad \text{(B-1)}$$

where

$\theta = t_P/(t_P + t_F)$,
t_P = past exposure time (i.e. baseline time),
t_F = future time,
$r = x_P + 0.5$,
x_P = number of observed events during the past exposure time, and
$\Gamma(x)$ = gamma function of x, which equals $(x$-$1)!$ (x factorial) if x is an integer.

All the above parameters must be greater than 0. The above distribution depends on the past data, x_P events in time t_P, and on the assumed future time during which events can occur, t_F . The distribution can be derived as a Bayesian distribution, assuming a gamma(0.5,0) prior distribution on the event frequency. This prior is the Jeffreys noninformative prior distribution.

The Poisson-gamma distribution (X) is related to the beta distribution (Y) through the following equation:

$$\Pr(X \geq x) = \Pr(Y \leq 1-\theta) \ , \qquad \text{(B-2)}$$

where Y has a beta(x, x_P) distribution. (See Johnson, Kotz, and Kemp 1992, Eq. 5.31.) Equation (B-2) allows easy computation of the upper tail probabilities by any computer package that has the beta distribution as a built-in function.

The potential early-warning thresholds mentioned in Section 2.1 are calculated using Equation (B-2) as 95% and 99% prediction limits on the future count. That is, the early-warning limit $x_{0.95}$ is the number such that $\Pr(X \geq x_{0.95}) \leq 0.05$. The early-warning limit $x_{0.99}$ is the number such that $\Pr(X \geq x_{0.99}) \leq 0.01$.

Thresholds determined from predictive distributions are counts of events. These counts can be converted into occurrence rates by dividing the count by the appropriate prediction period time.

B.1.2 Integrated Indicator

The integrated indicator is given by Equation (5) in Section 3.3. Within that equation, each λ_i is estimated from the observed count x_i, as explained in Section 3.5. Therefore, the predictive distribution for the integrated indicator was found as follows.

Simulate each x_i from its predictive distribution. For example, generate N = 100,000 values of each x_i from its predictive distribution. For each run from 1 to N do the following:

- For each x_i calculate the corresponding estimate λ_i.

- Combine the various estimates (nine for BWRs, ten for PWRs) to produce the integrated indicator.

In this way, N simulated values of the integrated indicator are produced. These values are sorted, and the 95th percentile of the simulated values is taken as the early warning prediction limit.

B.1.3 Discussion

Several comments are in order for all the prediction limits presented above.

- The 95% prediction limit can be exceeded up to 5% of the time just from randomness alone, even if nothing in the process has changed. If 20 distinct indicators are monitored, it would not be surprising for one of them to exceed its 95% prediction limit. If this limit is used as the early-warning threshold, a process that is perfectly stable could still occasionally produce early warnings. This is an advantage of the integrated limit — it reduces the number of indicators down to two.

- The prediction limits for raw event counts are statistical. Early-warning thresholds based on these limits correlated with risk, but are not derived from consideration of a specific risk level. The integrated indicators make the connection to risk, because their units are those of core damage frequency.

- The current results are preliminary, as has been mentioned above. An expert panel will determine the final thresholds.

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APPENDIX C

Initiating Event Trend Plots and Prediction Limits

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APPENDIX C – INITIATING EVENT TREND PLOTS AND PREDICTION LIMITS

In this appendix, trend plots and predictive limits for the risk-significant initiating events are presented. Each plot contains the fiscal year values, the estimated trend line, and 95th and 99th percentiles of the predictive distribution.

C.1 LIST OF INITIATING EVENTS

The initiating event study (NUREG/CR-5750) provides data for a large number of initiating event types. A subset of these types has been identified as being risk significant (NUREG-1753). The list of initiating events considered is presented in Table 1.

Table C-1 Risk Significant Initiating Events

Loss of Offsite Power Loss of Safety-Related Vital AC Bus Loss of Safety-Related Vital DC Bus Small/Very Small Loss of Coolant Accident General Transients Loss of Feedwater Loss of Heat Sink
BWR Loss of Instrument Air/Control Air BWR General Transients BWR Stuck Open Safety/Relief Valve BWR Loss of Heat Sink
PWR Loss of Instrument Air/Control Air PWR General Transients PWR Loss of Heat Sink PWR Stuck Open Safety/Relief Valve PWR Steam Generator Tube Rupture

There is some overlap in the initiating events listed above. The General Transients category includes both BWR General Transients and PWR General Transients. Also, the Loss of Heat Sink category includes both BWR and PWR Losses of Heat Sink. If these two categories are eliminated, then there is no overlap among the other categories.

C.2 CHOICE OF BASELINE PERIODS

For each initiating event considered, a baseline period must be established. The baseline period is used to determine a baseline value for the initiating event. Also, the baseline period data are then used as input to the predictive limits analysis.

The baseline period should have the following desirable characteristics:

- The baseline period is long enough to give a good estimate of the frequency, not strongly influenced by random variation.

- The baseline period is short enough that the true frequency is approximately constant during the entire period.

- The baseline period minimizes the resulting upper prediction limits.

Because of the first bulleted item, it was decided that every baseline period should contain at least four years. For each initiating event, the history was examined back to the earliest year of data, 1988. Candidate baseline periods were considered, starting in any year from the earliest year to 1998 and ending in 2001. (Because of the requirement for at least four years of data, 1998 is the latest starting year allowed, given data through 2001.) For each candidate baseline period, a trend model was fitted to the data, and the p-value for testing the no-trend model was calculated. In this way, each candidate starting year was assigned a corresponding p-value. A $p\text{-value} > 0.2$ was regarded as showing little evidence of a trend during the period. The baseline period was selected to balance the competing criteria shown with the above bullets. Both the visual plot and the p-values were used in the decision.

C.3 TRENDING METHOD

Poisson regression is the appropriate model to use when the observable quantity is a count of events in time. Unplanned scrams, safety system actuations, and "significant events" are examples of such observable quantities.

In the discussion below, i indexes the years in the data set, with $i=1$ for the first year, $i=2$ for the second year, etc. X_i represents the observable quantity, such as an initiating-event count or a forced-outage rate, in year i.

The observable quantity X_i is assumed to be Poisson distributed. The mean of X_i is $\lambda \times t_i$, where t_i is a known "exposure time", such as reactor-critical-years during the year i. The unknown parameter λ is typically modeled as $\exp(a + b \times i)$, or equivalently, $\ln(\lambda) = a + b \times i$. The parameters can be estimated by maximum likelihood. Their associated uncertainties can also be estimated.

C.4 TRENDS AND PREDICTION LIMITS

Table C-2 contains the prediction limits thresholds for the initiating events listed in Table 1, as well as information used to specify the gamma-Poisson prediction distribution. The relatively large p-values suggest that the frequency is roughly constant during the baseline period, as desired. Figures C-1 through C-16 contain the trends and the 95^{th} and 99^{th} prediction limits for these initiating events.

Table C-2 Prediction Limits for Initiating Events

Risk Significant Initiating Event	Baseline Period Starting Year	Baseline Mean Frequency (per Plant per Critical Year)	Baseline Period Reactor Critical Years	Baseline Period Number of Events	Reactor Critical Years Assumed for One Year of Industry Operation	95% Prediction Limit (Industry Event Counts Over One Year)	99% Prediction Limit (Industry Event Counts Over One Year)	Slope Parameter P-Value
BWR Loss of Instrument Air	1994	0.0108	231.5	2	31.77	3	3	0.705
PWR Loss of Instrument Air	1990	0.0122	696.1	8	61.71	3	5	0.229
Loss of Vital AC Bus	1988	0.0275	1182.3	32	93.41	7	8	0.333
Loss of Vital DC Bus	1988	0.0030	1182.3	3	93.41	2	3	0.482
Loss of Offsite Power	1997	0.0125	439.4	5	93.41	4	6	0.613
Small LOCA	1988	0.0047	1182.3	5	93.41	3	4	0.396
PWR Steam Generator Tube Rupture	1988	0.0044	800.6	3	61.71	2	3	0.776
General Transients	1998	0.807	358.7	289	93.41	93	100	0.368
BWR General Transients	1997	0.895	146.9	131	31.77	39	44	0.566
PWR General Transients	1998	0.794	239.0	182	61.71	61	67	0.625
Loss of Feedwater	1993	0.102	785.4	80	93.41	16	19	0.726
Loss of Heat Sink	1995	0.127	617.1	78	93.41	19	22	0.574
BWR Loss of Heat Sink	1996	0.190	176.2	33	31.77	12	14	0.679
PWR Loss of Heat Sink	1991	0.0974	641.9	62	61.71	12	14	0.614
BWR Stuck Open SRV	1993	0.0213	258.2	5	31.77	3	4	0.645
PWR Stuck Open SRV	1988	0.0031	800.6	2	61.71	2	3	0.556

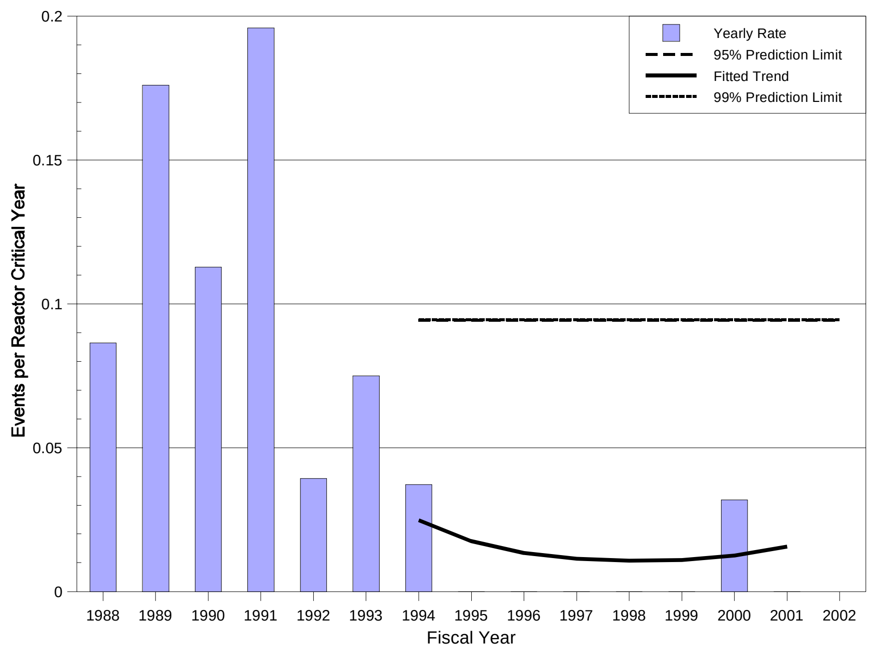

Figure C-1 BWR loss of instrument air. The trend is not statistically significant (p-value = 0.705).

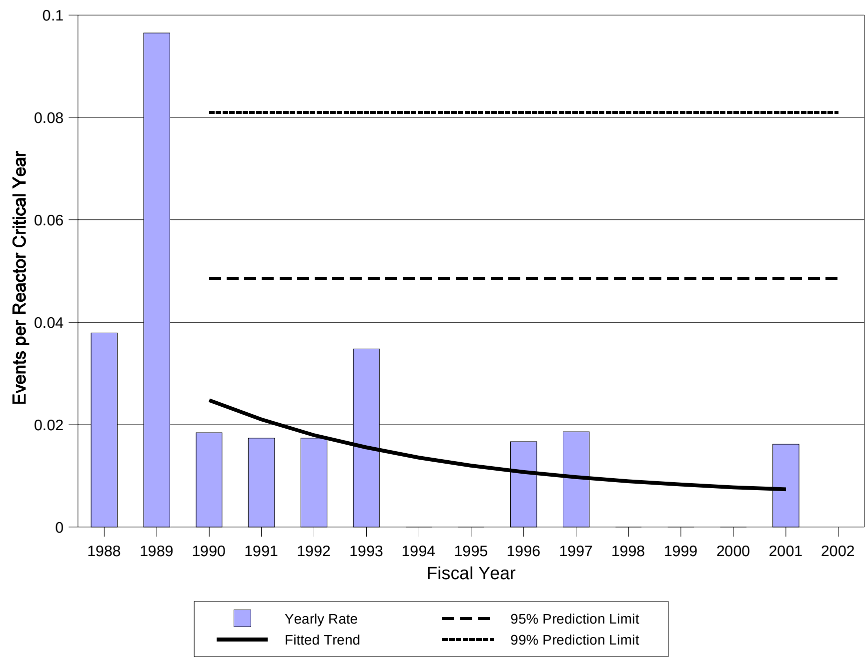

Figure C-2 PWR loss of instrument air. The trend is not statistically significant (p-value = 0.229).

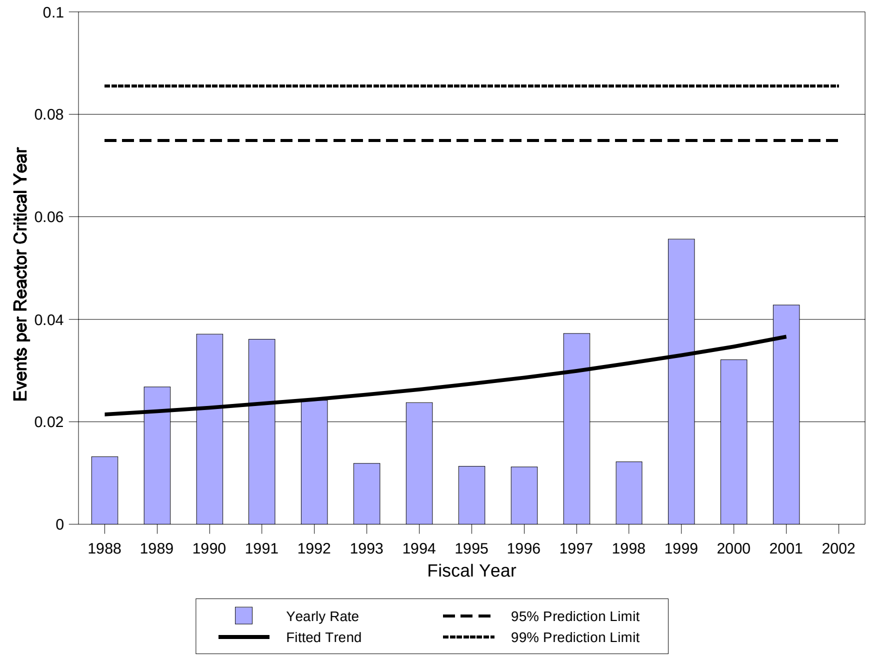

Figure C-3 Loss of vital AC bus. The trend is not statistically significant (p-value = 0.333).

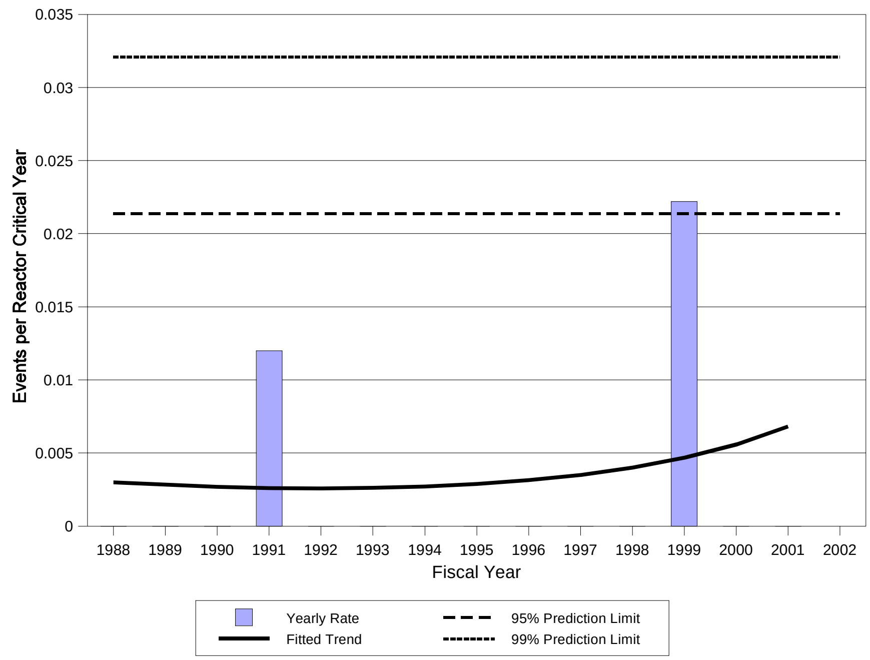

Figure C-4 Loss of vital DC bus. The trend is not statistically significant (p-value = 0.482).

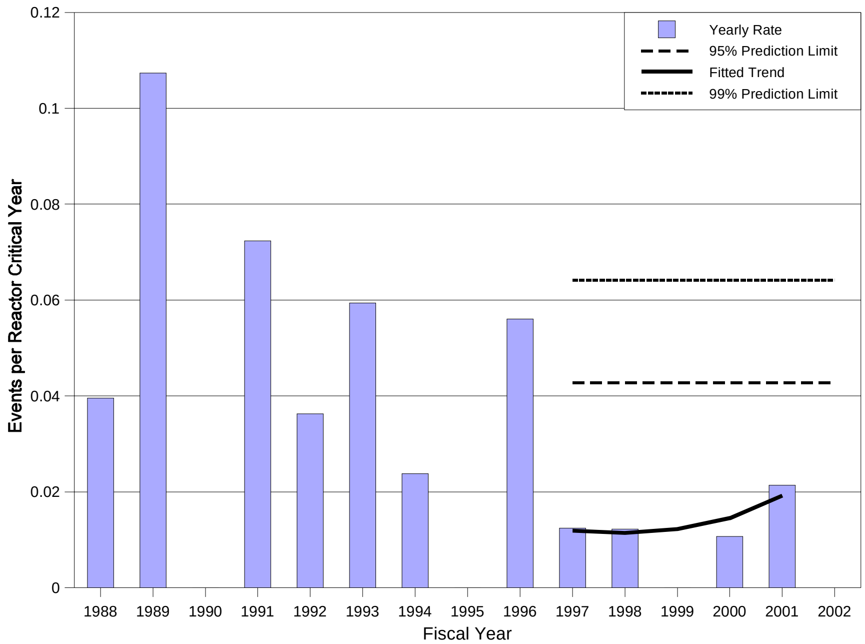

Figure C-5 Loss of offsite power. The trend is not statistically significant (p-value = 0.613).

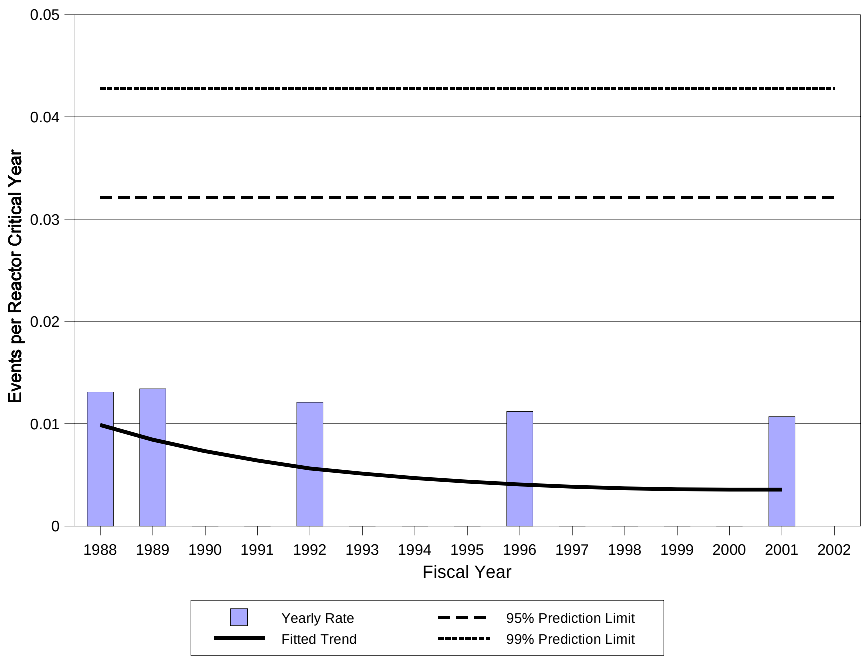

Figure C-6 Small/very small loss of coolant accident. The trend is not statistically significant (p-value = 0.396).

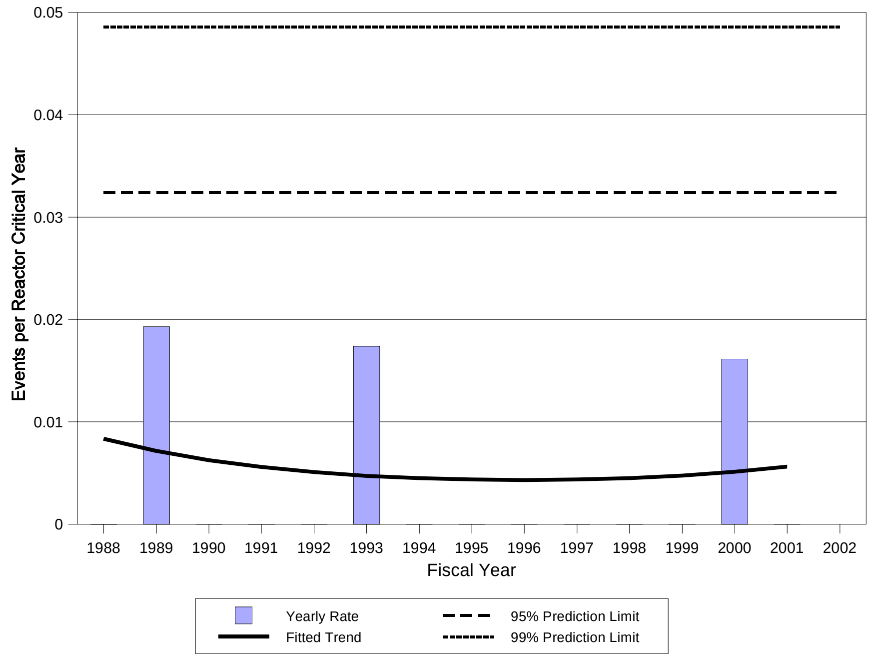

Figure C-7 PWR steam generator tube rupture. The trend is not statistically significant (p-value = 0.776).

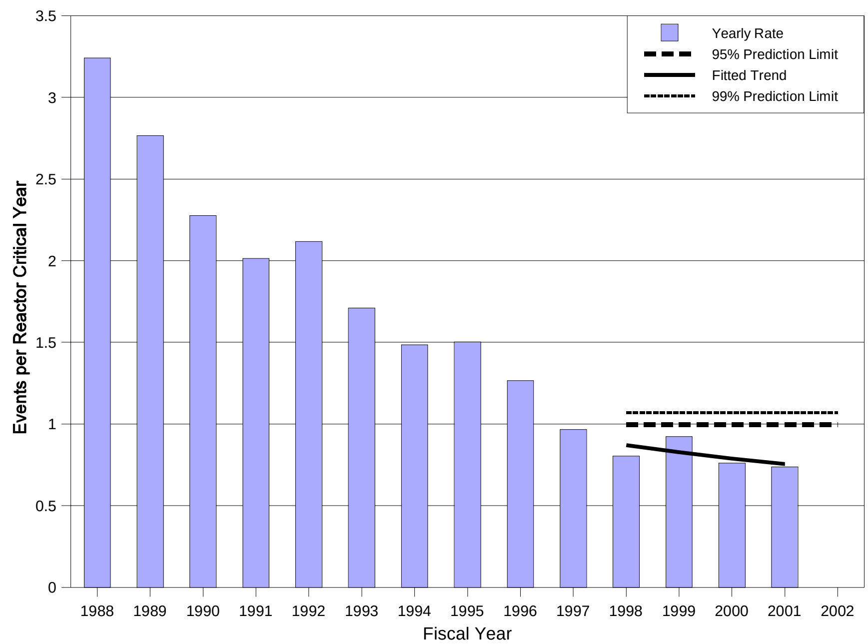

Figure C-8 General transient initiating events. The trend is not statistically significant (p-value = 0.368).

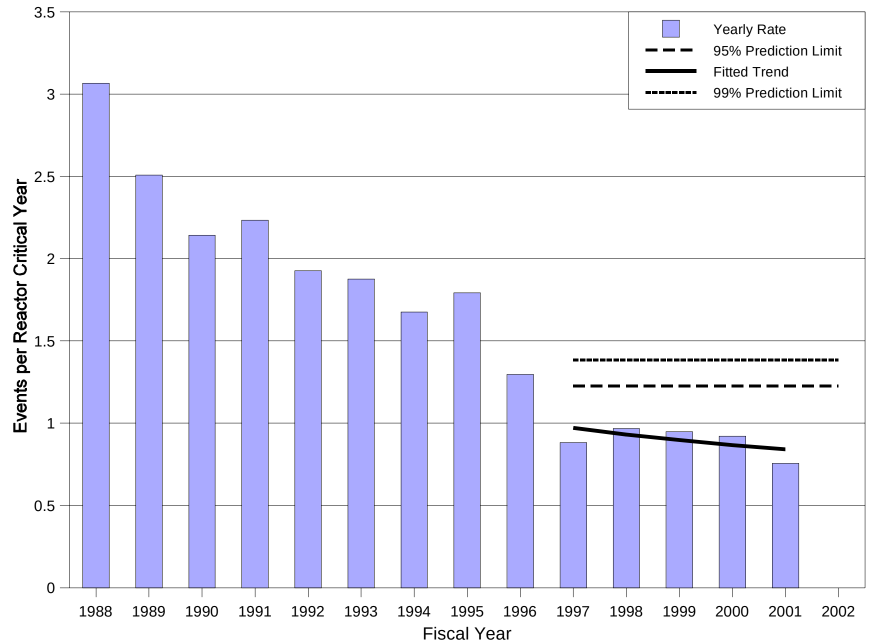

Figure C-9 BWR general transients initiating events. The trend is not statistically significant (p-value = 0.566).

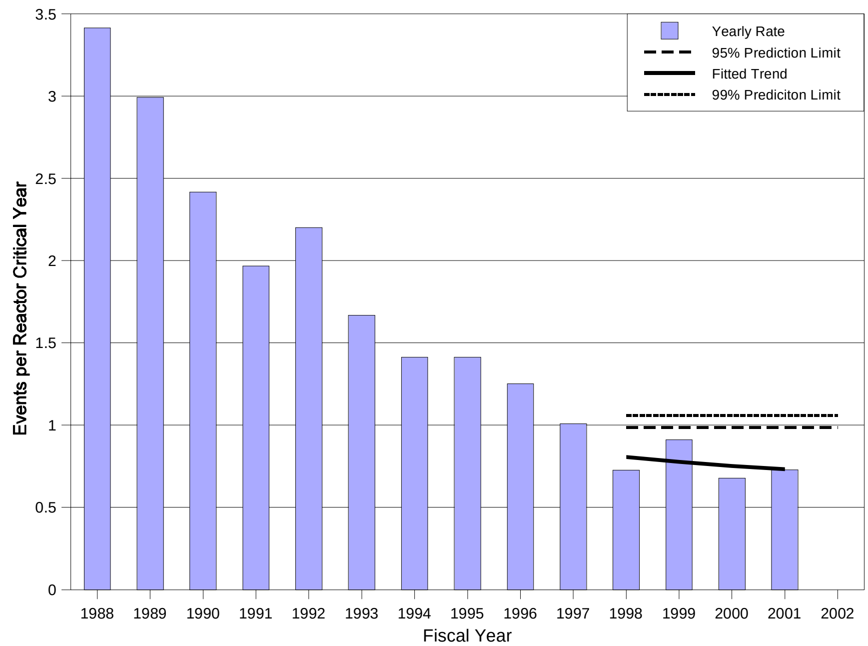

Figure C-10 PWR general transient initiating event. The trend is not statistically significant (p-value = 0.625).

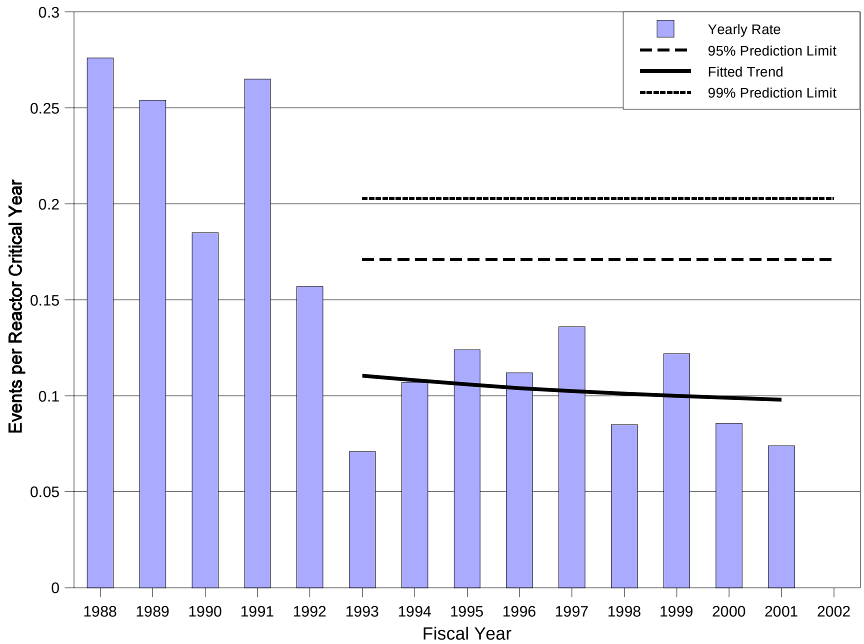

Figure C-11 Loss of feedwater initiating event. The trend is not statistically significant (p-value = 0.726).

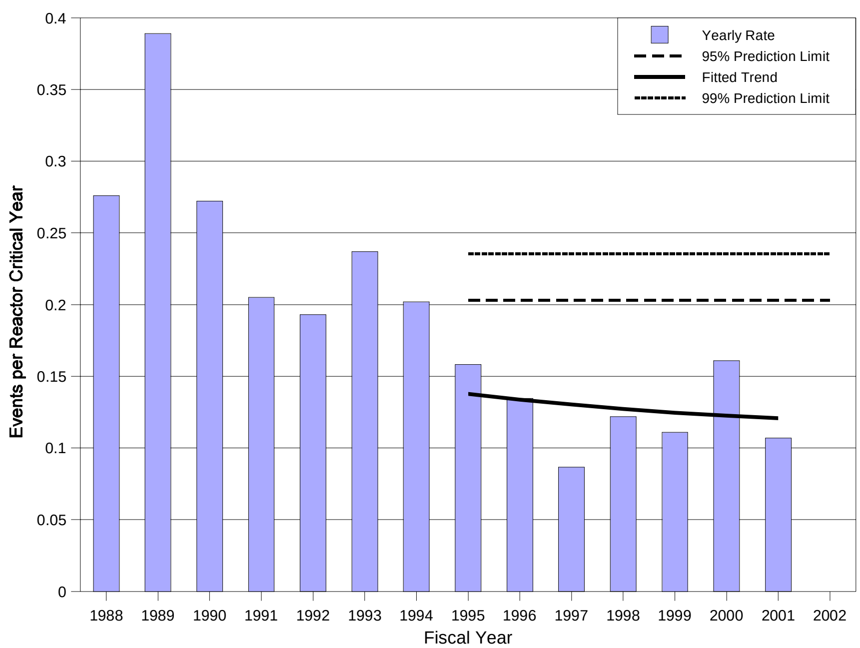

Figure C-12 Loss of heat sink. The trend is not statistically significant (p-value = 0.574)

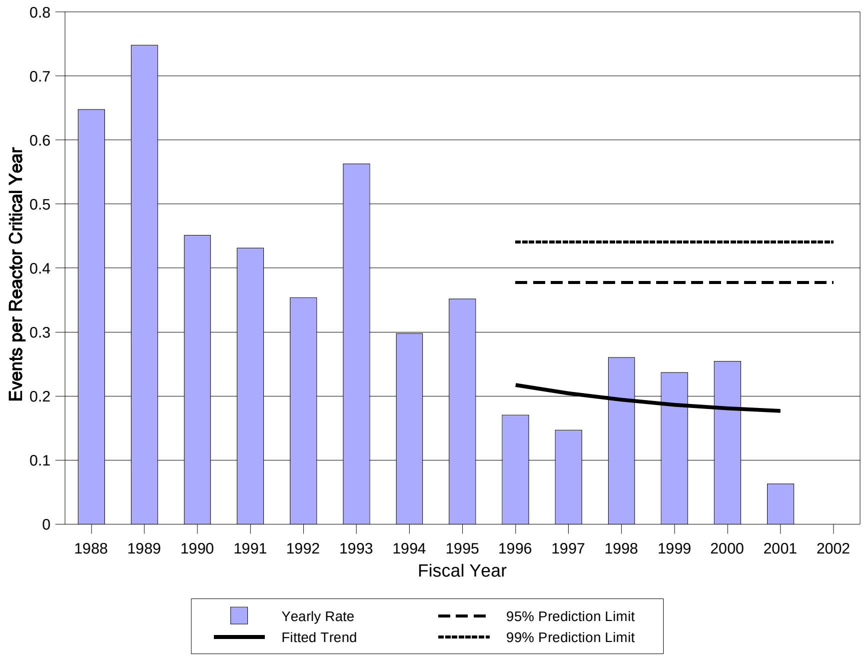

Figure C-13 BWR loss of heat sink. The trend is not statistically significant (p-value = 0.679).

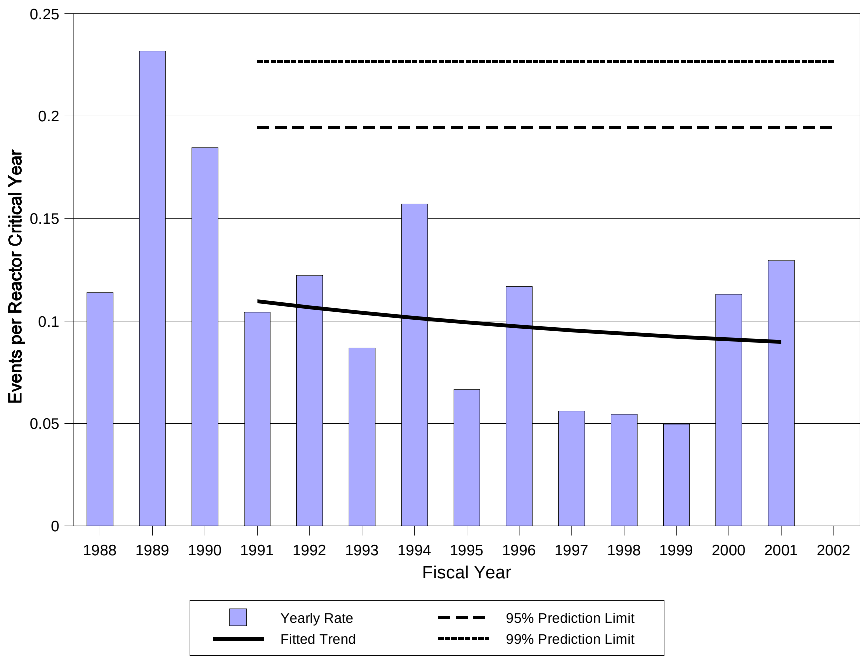

Figure C-14 PWR loss of heat sink. The trend is not statistically significant (p-value = 0.614).

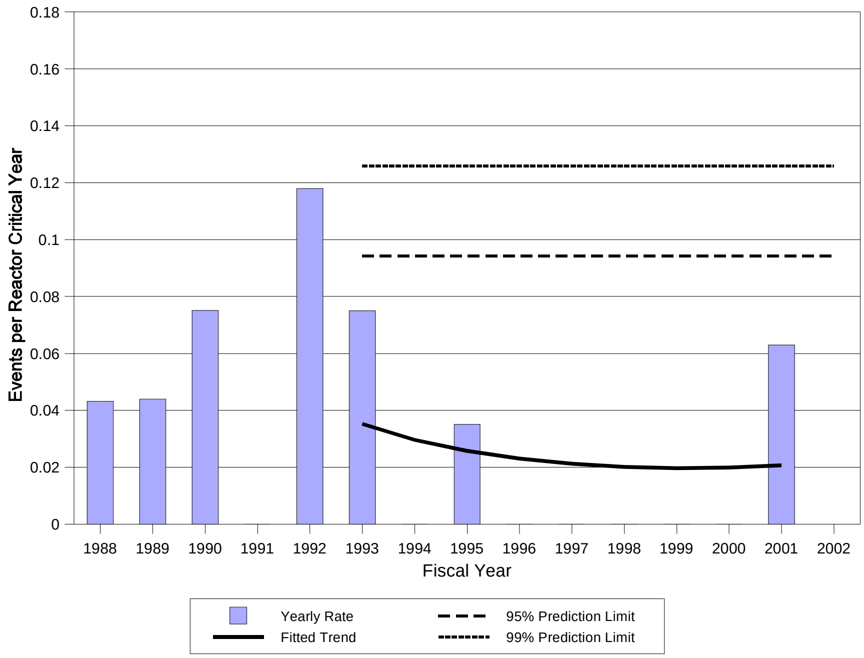

Figure C-15 BWR stuck open safety/relief valve. The trend is not statistically significant (p-value = 0.645).

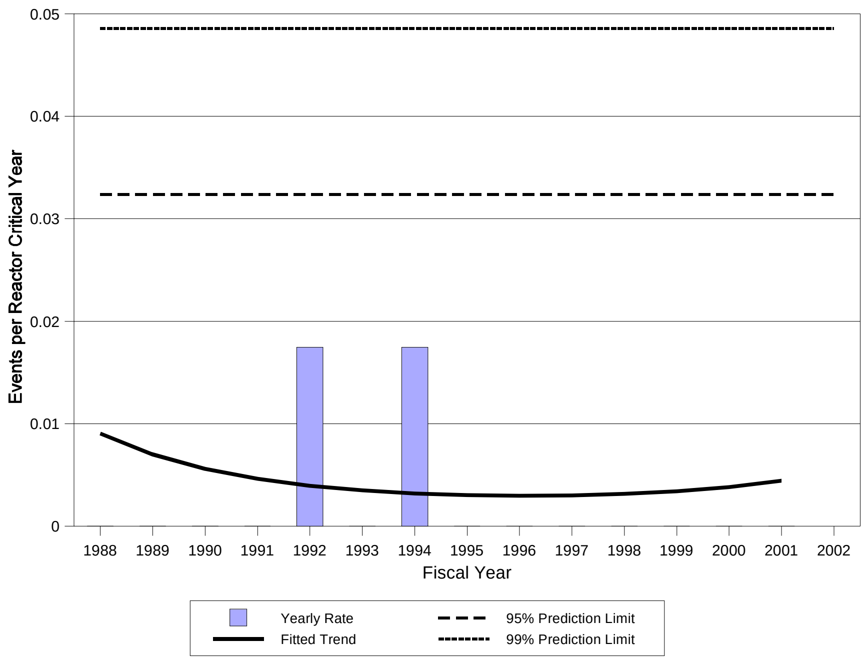

Figure C-16 PWR stuck open safety/relief valve. The trend is not statistically significant (p-value = 0.556).

APPENDIX D

Initiating Event Birnbaum Importance Measures

INITIATING EVENT BIRNBAUM IMPORTANCE MEASURES

The integrated industry initiating event indicator (IIIEI) requires Birnbaum importance measures for each of 10 types of initiating events. The initiating events are listed in Table 1 of Section 3. Birnbaum estimates were obtained from the Standardized Plant Analysis Risk (SPAR) Revision 3i models of U.S. commercial nuclear power plants. These SPAR models cover at power, internal event core damage frequency (CDF). Contributions to CDF from shutdown and from external events are not included at this time. There are 72 SPAR models covering the 103 operating plants (34 boiling water reactors or BWRs, and 69 pressurized water reactors or PWRs).

The SPAR Rev. 3i models are being converted to SPAR Rev. 3 models. The Rev. 3 model is a Rev. 3i model that has been revised based on results from a recent plant visit (to review the model and results with the licensee's PRA staff and benchmark it against the licensee's PRA for the plant). This process is scheduled to be completed by the end of calendar year 2003. When all of the Rev. 3i models have been converted to Rev. 3 models, the Birnbaum estimates should be revised.

The IIIEI measures the change in CDF, or ΔCDF, resulting from changes in individual initiating event frequencies. For a given initiator, the ΔCDF is the Birnbaum times the change in initiator frequency (current value minus baseline value). If initiating event frequencies are presented as events per critical year, then the IIIEI has units of ΔCDF per critical year.

At the time this work was done (August 2002), there were 32 BWR plants covered by SPAR Rev. 3i models (excluding Millstone 1, which has been permanently shut down). The Birnbaum importance measures and/or cut set slicing results were obtained for each of these 32 models. (Cut set slicing refers to identifying a subset of the cut sets contributing to the overall CDF and determining the contribution to CDF from this subset.) Results for a given initiator were summed and then divided by 32 to obtain an average Birnbaum importance per plant. Results are presented in Table D-1.

There were 60 PWR plants covered by SPAR Rev. 3i models at the time this work was done. The Birnbaum importance measures for a given initiator were summed and divided by 60 to obtain an average Birnbaum importance per plant. Results are presented in Table D-1.

After all the SPAR 3i models have been converted to SPAR Rev. 3, the current plans are to update and improve the models in the following areas:

- Initiating event frequencies,
- Basic event failure probabilities,
- Treatment of loss of offsite power,
- Treatment of steam generator tube rupture, and
- Human reliability failure probability estimates.

Table D-1 Initiating event Birnbaum importance measures

Initiating Event	Birnbaum Importance [a]		Initiator Modeled Explicitly in SPAR?	Birnbaum Importance Obtained How?	Comments
	BWRs	PWRs			
Loss of Instrument Air	8.20E-6	8.35E-5	Yes	Directly from SPAR output	
Loss of Vital AC Bus	Not available	Not available	Yes	Directly from SPAR output	SPAR modeling guidelines include this initiator if it is risk significant at the plant in question. However, none of the existing SPAR models include this initiator.
Loss of Vital DC Bus	2.70E-4	2.99E-3	Yes	Directly from SPAR output	PWR results dominated by 4 plants (out of 60 covered by SPAR models).
Loss of Offsite Power	3.22E-4	3.25E-4	Yes	Directly from SPAR output	
Small LOCA	5.62E-5	2.52E-3	Yes	Directly from SPAR output	
Steam Generator Tube Rupture	Not applicable	7.89E-4	Yes	Directly from SPAR output	SPAR models for this initiator are thought to be conservative (result in high CDF estimates).
General Transients	1.36E-6	2.02E-6	Yes [b]	Cut set slicing	
Loss of Feedwater	1.45E-5	1.89E-5	No	Cut set slicing	
Loss of Heat Sink	8.44E-6	1.89E-5	No	Cut set slicing	
Stuck Open SRV	4.71E-5	6.36E-4	No	Cut set slicing	

a. Per plant

b. The general transient event tree has top events to also cover loss of feedwater, loss of heat sink, and stuck open SRV. Therefore, the Birnbaum obtained directly from the SPAR output for the general transient initiator reflects importances from four types of initiating events. To obtain the correct Birnbaum for the general transient initiator, cut set slicing was used.

APPENDIX E

IIIEI Simulation, Uncertainty, and Sensitivity Results

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E.1 OUTLINE

This appendix deals with several topics:

- Uncertainty in the integrated industry initiating event indicator (IIIEI) core damage frequency (CDF), resulting from uncertainty in the initiating event frequencies
    - Estimated baseline IIIEI (CDF) (industry mean)
    - Estimated current IIIEI (CDF) (industry mean)

- Predictive distribution of estimators of the current IIIEI (CDF), including determination of selected percentiles

- Identification of particular initiating events that contribute most to estimated CDF or its uncertainty, as a result of their high (industry mean) Birnbaum importances

- Investigation of the variation between plants in the Birnbaum importances, and the effect of this variation on plant-specific estimates of IIIEI (CDF).

Each of the above topics is considered, first for BWRs and then for PWRs.

E.2 INTRODUCTION

CDF can be expressed by the following equation:

$$CDF = \sum_{i=1}^{m} B_i \lambda_i \qquad \text{(E-1)}$$

where B_i is the partial derivative of CDF with respect to initiating event frequency λ_i, and i indexes the kind of initiating event, such as loss of offsite power (LOOP) or loss of heat sink, as explained in Appendix A. The partial derivative B_i is called the Birnbaum importance measure.

Each plant– technically, each SPAR model for a plant – has its own set of Birnbaum importances. Most of this document assigns the mean value from the various plants to B_i (i.e., a value determined as the arithmetic average of plant-specific values), one mean for boiling water reactors (BWRs) and one mean for pressurized water reactors (PWRs). Occasionally, however, the plant-specific Birnbaum importances are considered.

The initiating event frequencies λ_i are never known exactly; the baseline frequencies are estimated from baseline data, and the current frequencies are estimated from the most recent one or more years of data, x events in t reactor-critical years. In addition, the estimates may be of several forms, of which this document considers two:

- The maximum likelihood estimate (MLE), x/t.

- The Bayes posterior mean based on updating some prior. For estimating baseline frequencies, the Jeffreys noninformative prior is used, a gamma(0.5, b) distribution with $b = 0$. For estimating current frequencies, a constrained noninformative prior is used, a gamma(0.5, b) distribution, with 0.5/*b* equal to the estimated baseline frequency. Thus, the Bayes posterior distribution is gamma(x + 0.5, t + b) in either case, and the posterior mean is (x + 0.5)/(t + b).

In this document, a single initiating-event frequency is assumed to apply to all plants, for the following reasons. For rare events, such as LOOP, we can never see enough data to contradict the assumption of a common frequency. On the other hand, frequent events such as general transients generally contribute less risk of core damage; therefore, even if plant-specific frequencies were used the effect on IIIEI (CDF) would be minimal.

Uncertainty in this document always refers to the uncertainty in the initiating event frequencies. This document does not consider uncertainty in the values of the Birnbaum importances, although in fact those quantities are estimates based on data that were input to the SPAR models. **Between-plant variability** in this document always refers to variation in the Birnbaum importances from plant to plant. Each initiating event frequency is assumed to have a single value, the same at all plants.

E.3 BASELINE IIIEI (CDF)

The estimated baseline IIIEI (CDF)s are examined here, for BWRs and PWRs. The main contributors to the estimates and their uncertainties are identified. The estimated baseline IIIEI (CDF)s are given, and the uncertainties in the estimates are quantified.

E.3.1 BWR Baseline IIIEI (CDF)

Table E-1 shows the contributions to the mean and variance of the baseline IIIEI (CDF). That is, the various initiating event frequencies are quantified by Bayesian distributions with gamma form, yielding a Bayesian distribution for the baseline IIIEI (CDF). Elsewhere when the “baseline IIIEI (CDF)” is given as a number, it is the mean of this distribution.

The element in the *i*th row of the “Mean” column is of the form $B_i a_i/b_i$. Each element of the “Variance” column is of the form $B_i a_i/b_i^2$. From the “Total” row, the standard deviation of the Bayesian distribution of the IIIEI (CDF) is 1.86×10^{-6}. Thus, two standard deviations equal about 3.7×10^{-6}, and the true baseline IIIEI (CDF) should not be regarded as known more accurately than that.

The full Bayesian distribution can be obtained by simulation, which also yields percentiles of the distribution. In this way, the 5th and 95th percentiles of the baseline IIIEI (CDF) are shown to be 7.84×10^{-6} and 1.38×10^{-5}, all with units of events per reactor-critical year. (The third significant digit may be slightly inaccurate.) The Bayesian distribution of baseline CDF is shown in Figure E-1.

Table E-1 Breakdown of BWR Baseline IIIEI (CDF) by Initiating Event

Initiating Event	Mean (Baseline CDF)		Variance (Baseline CDF)		Baseline Prior, Gamma(*a*, *b*)		Mean Birnbaum Importance
					a	*b*	
Loss of Offsite Power	4.03E-6	38.4%	2.95E-12	85.6%	5.5	439.36	3.22E-4
BWR Loss of Heat Sink	1.60E-6	15.3%	7.69E-14	2.2%	33.5	176.21	8.44E-6
Loss of Feedwater	1.49E-6	14.2%	2.74E-14	0.8%	80.5	785.43	1.45E-5
BWR General Transients	1.22E-6	11.6%	1.13E-14	0.3%	131.5	146.89	1.36E-6
BWR Stuck Open SRV	1.00E-6	9.6%	1.83E-13	5.3%	5.5	258.18	4.71E-5
Loss of Vital DC Bus	7.99E-7	7.6%	1.83E-13	5.3%	3.5	1182.26	2.70E-4
Small LOCA	2.61E-7	2.5%	1.24E-14	0.4%	5.5	1182.26	5.62E-5
BWR Loss of Instrument Air	8.85E-8	0.8%	3.14E-15	0.1%	2.5	231.51	8.20E-6
IIIEI (CDF) Total	1.05E-5	100.0%	3.45E-12	100.0%			

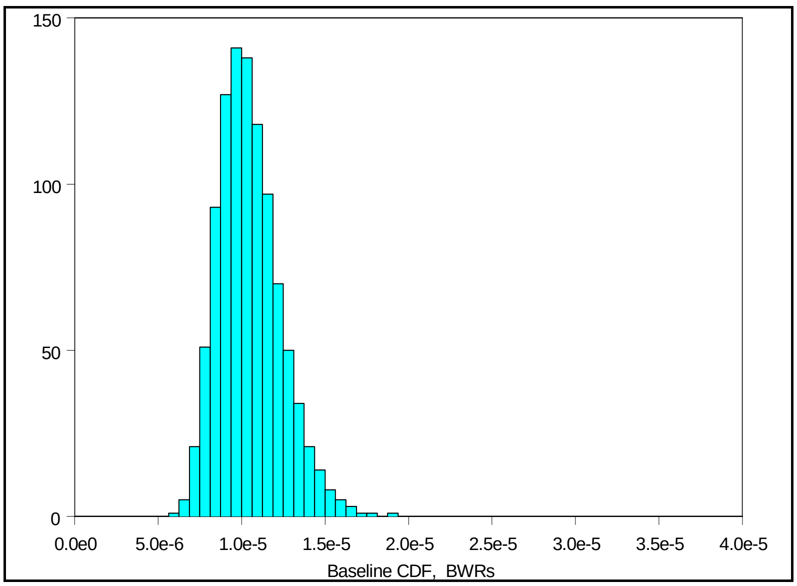

Figure E-1 Bayesian distribution of baseline CDF for BWRs

E.3.2 PWR Baseline IIIEI (CDF)

Table E-2 shows the same information for PWRs that is shown above for BWRs.

From the "Total" row, the standard deviation of the Bayesian distribution of the IIIEI (CDF) is 7.46×10^{-6}. Thus, two standard deviations equal about 1.5×10^{-6}, and the true baseline IIIEI (CDF) should not be regarded as known more accurately than that.

The full Bayesian distribution can be obtained by simulation. When this is done, the 5th and 95th percentiles of the baseline IIIEI (CDF) are found to be 2.54×10^{-5} and 4.99×10^{-5}, with units of events per reactor-critical year. (The third significant digit may be slightly inaccurate.) The Bayesian distribution of baseline IIIEI (CDF) is shown in Figure E-2.

Table E-2 Breakdown of PWR Baseline IIIEI (CDF) by Initiating Event

Initiating Event	**Mean (Baseline CDF)**		**Variance (Baseline CDF)**		**Baseline Prior, Gamma(*a*, *b*)**		**Mean Birnbaum Importance**
					a	***b***	
Small LOCA	1.17E-5	32.2%	2.50E-11	45.0%	5.5	1182.26	2.52E-3
Loss of DC Bus	8.85E-6	24.3%	2.24E-11	40.3%	3.5	1182.26	2.99E-3
Loss of Offsite Power	4.07E-6	11.2%	3.01E-12	5.4%	5.5	439.36	3.25E-4
PWR Steam Generator Tube Rupture	3.45E-6	9.5%	3.40E-12	6.1%	3.5	800.62	7.89E-4
PWR Stuck Open SRV	1.99E-6	5.5%	1.58E-12	2.8%	2.5	800.62	6.36E-4
Loss of Feedwater	1.93E-6	5.3%	4.66E-14	0.1%	80.5	785.43	1.89E-5
PWR Loss of Heat Sink	1.84E-6	5.0%	5.42E-14	0.1%	62.5	641.91	1.89E-5
PWR General Transient	1.54E-6	4.2%	1.30E-14	0.0%	182.5	238.97	2.02E-6
PWR Loss of Instrument Air	1.02E-6	2.8%	1.22E-13	0.2%	8.5	696.11	8.35E-5
IIIEI (CDF) Total	3.64E-5	100.0%	5.56E-11	100.0%			

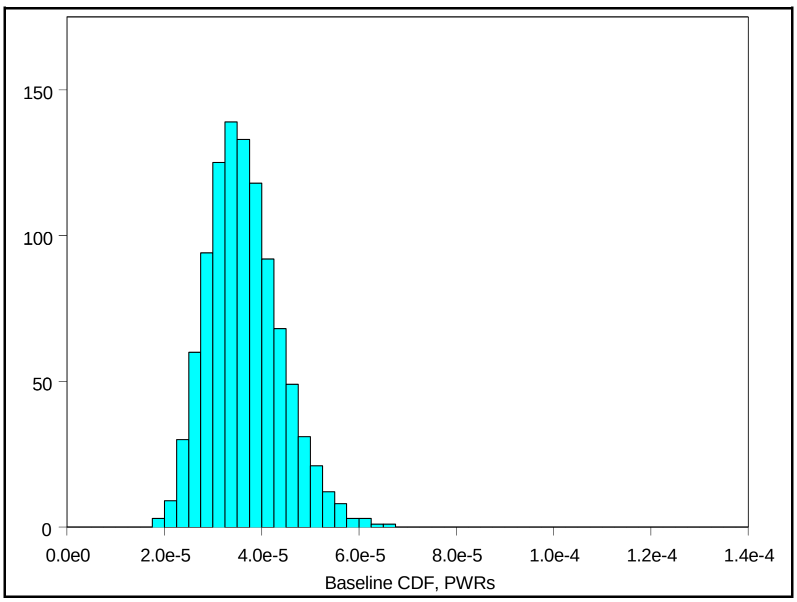

Figure E-2 Bayesian distribution of baseline CDF for PWRs

E.4 IIIEI (CDF) PREDICTIVE DISTRIBUTION

The IIIEI (CDF) is an estimate of CDF given by Equation (E-1), where B_i is the industry mean Birnbaum importance and the CDF has units of core damage events per reactor-critical year. The value of λ_i can be estimated in several ways, Bayesian or non-Bayesian based on varying amounts of data, as explained in Section E.2. The indicator is a random variable — different data counts result in different values of the IIIEI (CDF). Thus, we can construct the **predictive distribution** of the IIIEI (CDF), as follows.

Consider a single kind of initiating event, and two time periods, the baseline period, and the current data window.

The baseline period gives rise to a Bayesian distribution for λ. In particular, the Jeffreys noninformative prior distribution is assumed, a gamma(0.5, 0) distribution. If x_{base} initiating events were seen in t_{base} reactor-critical years, the posterior distribution of λ is gamma(x_{base} + 0.5, t_{base}). Denote this posterior distribution by $g(\lambda \mid x_{base}, t_{base})$. As a slight digression, we can note that the baseline distributions of Figures E-1 and E-2 are obtained by assigning these posterior distributions to the parameters λ_i in Equation (E-1).

The current data window is about to occur, so we ask how many initiating events of each type might be seen, and what values of IIIEI (CDF) they might lead to. The number of events, X_{new}, in the current data time period, t_{new}, is a Poisson(λt_{new}) random variable. Denote this distribution by

$$f(x \mid \lambda, t_{new}) = \Pr(X_{new} = x) = \exp(-\lambda t_{new})(\lambda t_{new})^x/x!.$$

Because λ is not known exactly, the predictive distribution of X is

$$f(x|x_{base}, t_{base}, t_{new}) = \int f(x|\lambda, t_{new})\, g(\lambda|x_{base}, t_{base})\, d\lambda \ .$$

This predictive distribution is discussed more fully by Atwood (2002), where it is advocated over several other possible definitions of predictive distributions.

Based on data from the current window, λ will be estimated, for example by the MLE, X_{new}/t_{new}, or by a Bayesian estimator. Let λ^* denote the estimator of λ. Thus, the predictive distribution for X_{new} defines a corresponding predictive distribution for λ^*. When these distributions are constructed for each type of initiating event, they result in a distribution for

$$\text{IIIEI (CDF)} = \sum_i B_i \lambda_i^* \ .$$

This is the **predictive distribution for IIIEI**.

The predictive distribution for IIIEI (CDF) is evaluated by simulation. That is, for each kind of initiating event, simulate many values of X_{new} from its predictive distribution. Calculate the resulting values of IIIEI (CDF), and observe the resulting mean, variance, and percentiles. The histograms below are obtained in this way, simulating 200,000 values of IIIEI for each graph. This is a large enough sample so that the 50th, 95th, and 99th percentiles are all accurate to about two significant digits. To make comparisons easier, the figures in each section below all have the same size and shape, the same axis limits, and the same size histogram bins.

The predictive distribution assumes that the process is unchanged between the baseline period and the current data window. Thus, observed values that are in the extremes of the predictive distribution are indicative of a change in the process.

E.4.1 Predictive Distributions of IIIEI (CDF) for BWRs

Figure E-3 shows the predictive distribution of IIIEI (CDF) for BWRs, when each λ_i is estimated by the maximum likelihood estimate x_i/t_i, and the current data window contains one industry year of data (31.97 reactor-critical years).

Figure E-3 shows a pronounced multimodality. The reason is that IIIEI (CDF) for BWRs is very sensitive to LOOP, as suggested by the baseline calculations in Table E.1. The four peaks in Figure E-3 correspond to observing 0, 1, 2, or 3 LOOP events during the data window. The variation within each peak corresponds to possible variation in the number of initiating events other than LOOP. Many people would not consider this distribution satisfactory. For example, the 90th percentile of the distribution is 2×10^{-5}. If this percentile were used as a threshold, rather than calculating the IIIEI one could simply note whether two or more LOOP events had occurred. The values above the 90th percentile correspond almost exactly to the cases with two or more LOOP events. To reduce the dependence on a single kind of initiating event, we now consider using three years of data, which is shown in Figure E-4. This distribution shows much less multimodality.

We now consider versions of the IIIEI (CDF) that use Bayesian estimators of the parameters. The prior is taken to be the constrained noninformative prior with the industry baseline mean. This is a gamma(a, b) distribution with a = 0.5 and b such that the prior mean, a/b, is equal to the industry baseline mean. See Atwood (1996) for a justification of this prior. The baseline means can be calculated as a/b from the values in the columns for the baseline prior in Table E-1.

Figures E-5 and E-6 contain the distributions for the Bayesian estimators using one year and three years of current data, respectively. As can be seen, the Bayes distributions are less multimodal, that is, less sensitive to the number of occurrences of any single kind of initiating event. Based on the criterion of avoiding multimodality, the most desirable indicator uses Bayes estimators with three years of data. The 95th percentile of this distribution is 1.63×10^{-5}, and the 99th percentile is 1.97×10^{-5}, both with units of events per reactor-critical-year.

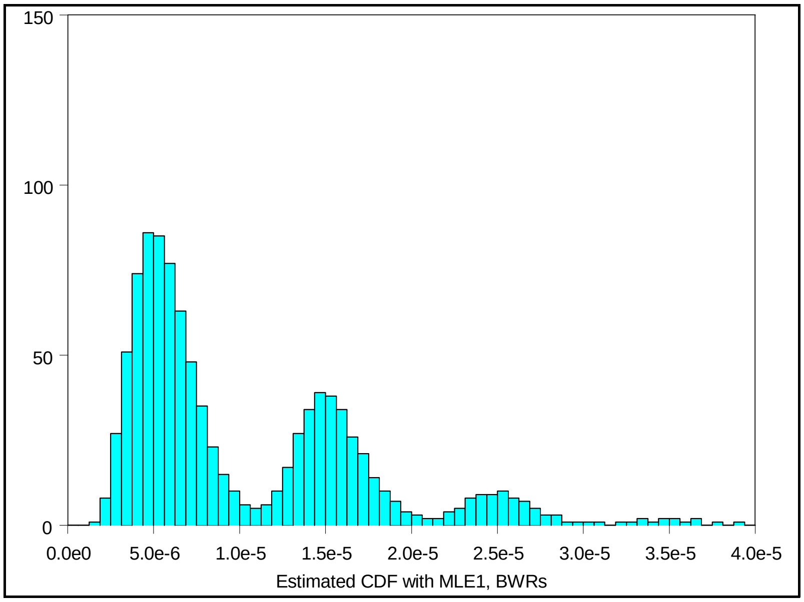

Figure E-3 Predictive distribution of IIIEI for BWRs, when MLE is used with one year of data.

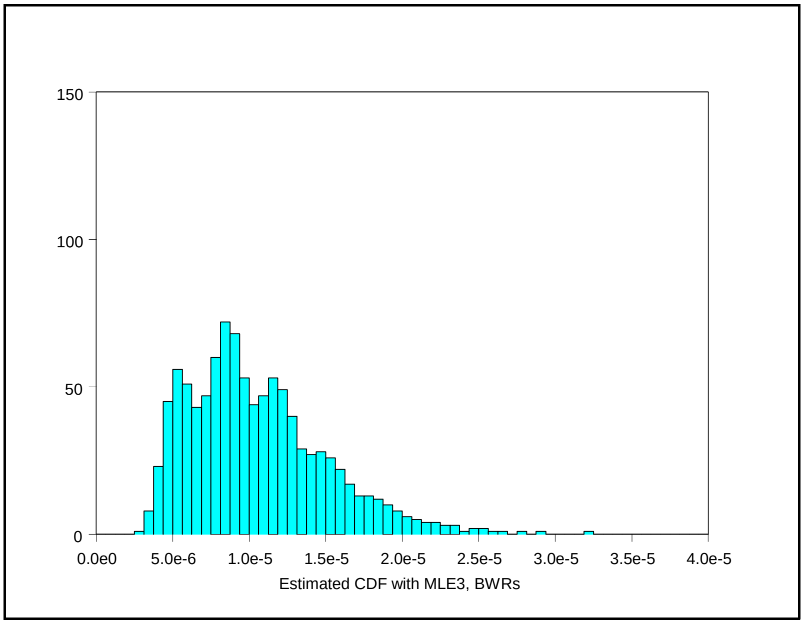

Figure E-4 Predictive distribution of IIIEI for BWRs when MLE is used with three years of data

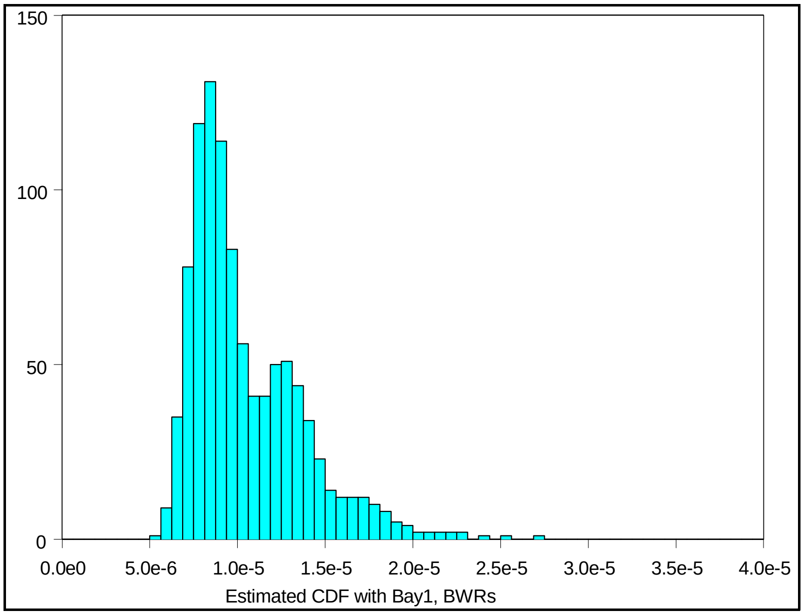

Figure E-5 Predictive distribution of IIIEI for BWRs, when using Bayes estimator with one year of data

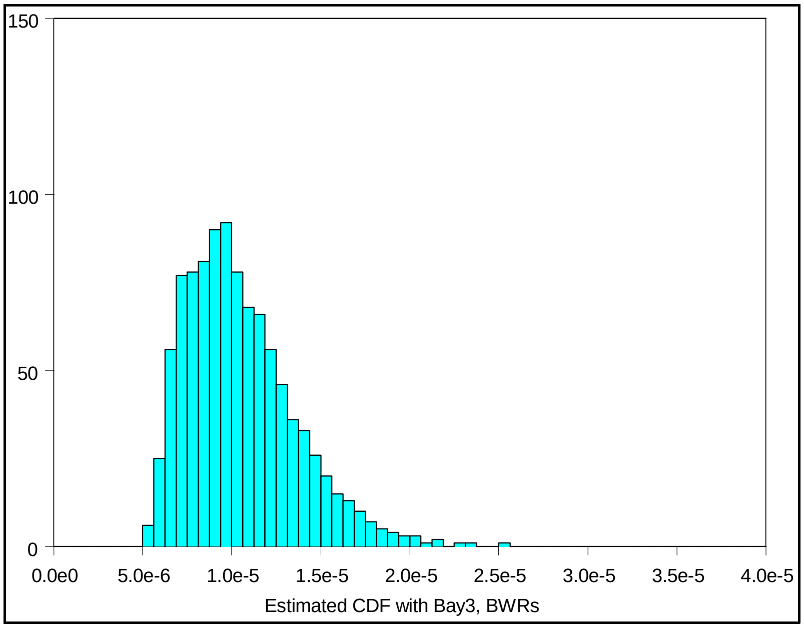

Figure E-6 Predictive distribution of IIIEI for BWRs, when using Bayes estimator with three years of data

E.4.2 Predictive Distribution of IIIEI (CDF) for PWRs

The same type of information is now given for PWRs. The first distribution assumes that each λ_i is estimated by the MLE, with the data window equal to one industry year (62.76 reactor-critical years).

Figure E-7 shows the distribution when the MLE is used with one year of current data. As in Figure E-3, the analogue for BWRs, this distribution shows multimodality. In this case, the large hump to the left of 4.0×10^{-5} corresponds to no occurrences of Small/Very Small LOCA or of Loss of Vital DC Bus. The next hump, between 4.0×10^{-5} and 8.0×10^{-5}, corresponds to exactly one occurrence of either of those events. The next hump corresponds to two occurrences of these events (two of either one or one of each). As is seen in Figure E-8 below, this multimodality is greatly reduced when the current data window is made larger.

Use of Bayesian estimators reduces the multimodality even more, as shown in Figures E-9 and E-10. As with BWRs, the prior used for each frequency is the constrained noninformative prior with the baseline mean.

Based on the criterion of unimodality, the final distribution is most desirable, corresponding to use of Bayes estimation with a three-year data window. The 95^{th} and 99^{th} percentiles of this distribution are 5.79×10^{-5} and 7.05×10^{-5}, both with units of core damage events per reactor-critical-year.

E.4.3 Final comments

For all the above calculations, a BWR industry year was assumed to equal 31.97 reactor-critical-years, and a PWR industry year was assumed to equal 62.76 reactor-critical-years. These were the values actually observed in FY 2002, the first year following the baseline periods. Before any part of the current data window had been observed, the number of reactor-critical-years in a data window would have had to be estimated from the baseline data. The final year of the baseline periods, FY 2001, had 31.77 BWR-critical-years and 61.71 PWR-critical-years. When the distributions were simulated assuming these time periods, the resulting 95^{th} and 99^{th} percentiles differed at most in the third significant digit from the percentiles given above.

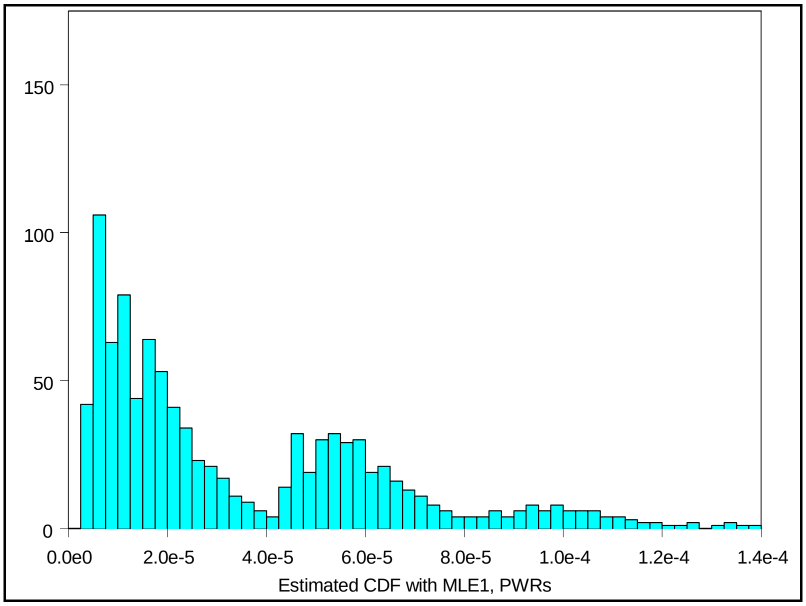

Figure E-7 Predictive distribution of IIIEI for PWRs, when using MLE with one year of data

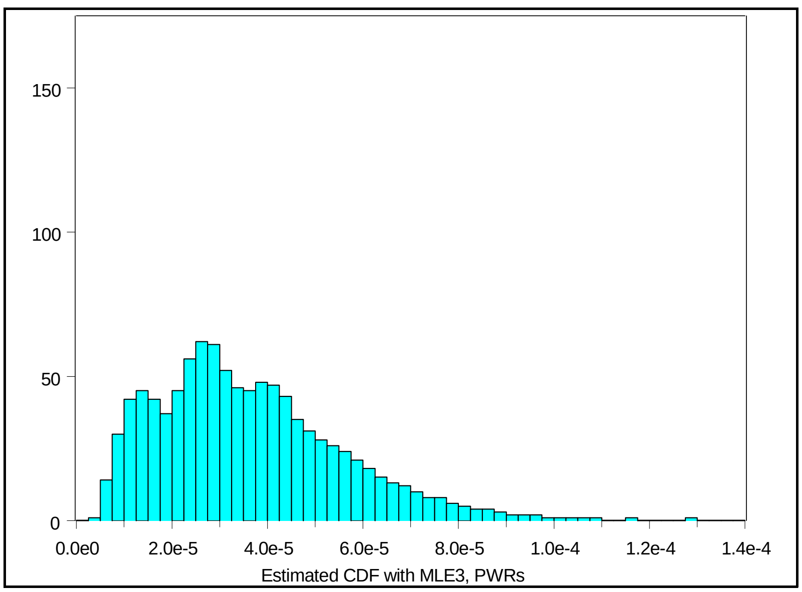

Figure E-8 Predictive distribution of IIIEI for PWRs, when using MLE with three years of data..

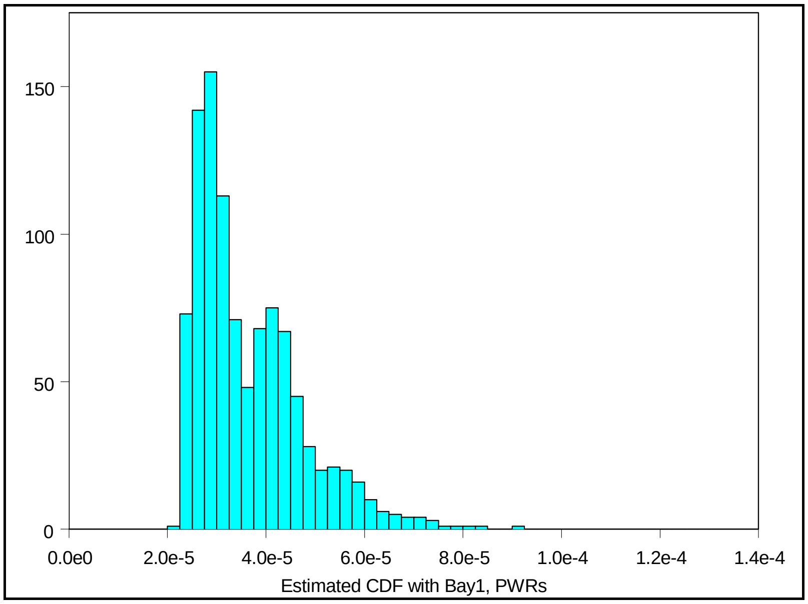

Figure E-9 Predictive distribution of IIIEI for PWRs, when using Bayes estimator with one year of data

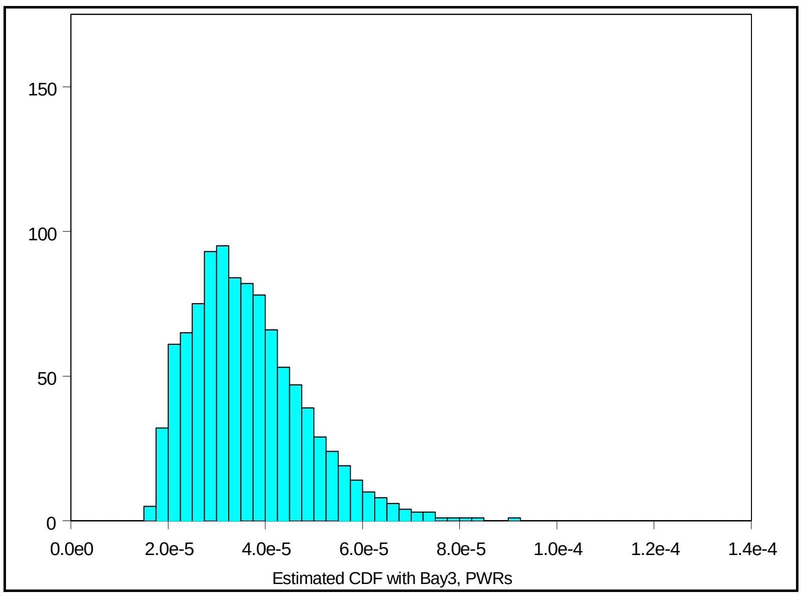

Figure E-10 Predictive distribution of IIIEI for PWRs, when using Bayes estimator with three years of data

E.5 PLANT-SPECIFIC CONSIDERATIONS

The above calculations have used industry-average Birnbaum importances, corresponding to a hypothetical “representative” reactor. This is appropriate for work performed under the Industry Trends Program. However, the Birnbaum importances do vary from plant to plant. The size of this variation and its consequence are discussed here.

E.5.1 Variation of Birnbaum Importances Among BWRs

The plant-specific IIIEI (CDF) is shown in Figure E-11. This is calculated using Equation E-1, with a single frequency for each kind of initiating-event, applicable at all plants, and plant-specific Birnbaum importances. These are shown for the 32 BWRs with analyzed SPAR models. (There are now 34 SPAR BWR models, covering all of the operating BWRs.)

As shown in Table E-1, the dominant initiating event for BWRs is LOOP. Therefore, it can be expected that the most extreme plant in Figure E-11 has an outlying Birnbaum importance for LOOP. In Figure E-12, the extreme value on the right corresponds to a single BWR, the same plant in both figures. The match between Figures E-11 and E-12 breaks down for the other plants – the second largest plant in Figure E-11 is different from the second largest plant in Figure E-12.

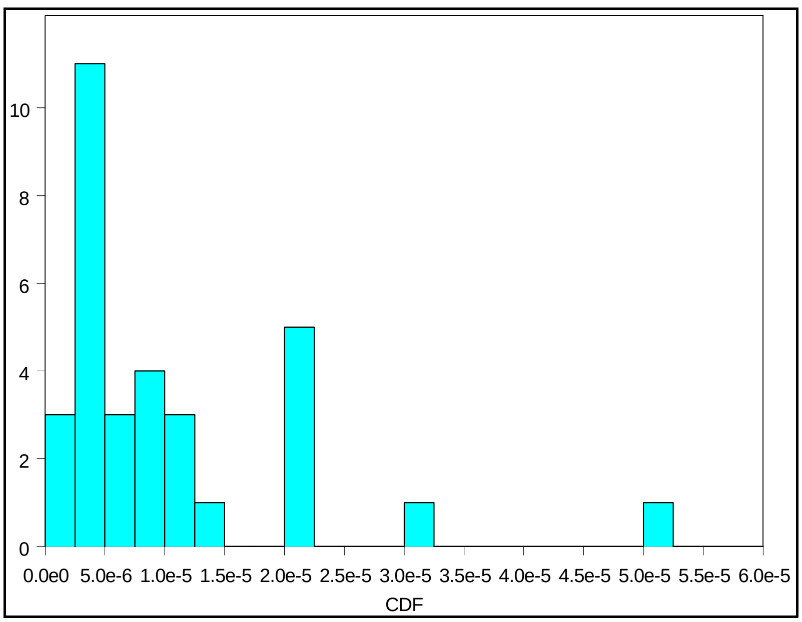

Figure E-11   Baseline CDF at 32 BWRs

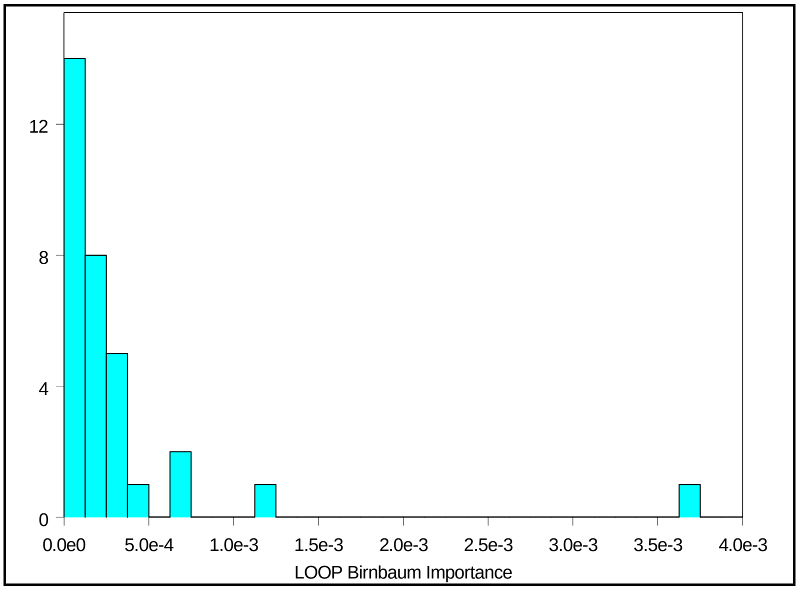

Figure E-12 Birnbaum importance of LOOP, for 32 analyzed BWRs

E.5.2 Variation of Birnbaum Importances Among PWRs

The plant-specific IIIEI (CDF) is shown in Figure E-13. Just as for BWRs in Section E.5.1, this is calculated using Equation (E-1), with a single frequency for each kind of initiating-event, applicable at all plants, and plant-specific Birnbaum importances. It is plotted for the 60 PWRs with SPAR models. (There are now 69 SPAR PWR models, covering all operating plants.)

The outlying values on the right correspond to the two units at a single station (having the same SPAR model). The next smallest values, approximately 8×10^{-5}, correspond to two other two-unit stations. From Table E.2, it might be anticipated that these plants have high Birnbaum importances for Small/Very Small LOCA or Loss of Vital DC Bus. These two Birnbaum importances are shown in Figures E-14 and E-15. The outlying plants for Small/Very Small LOCA are the most extreme two plants in Figure E-13. The outlying plants for Loss of Vital DC Bus are the next four most extreme plants in Figure E-13.

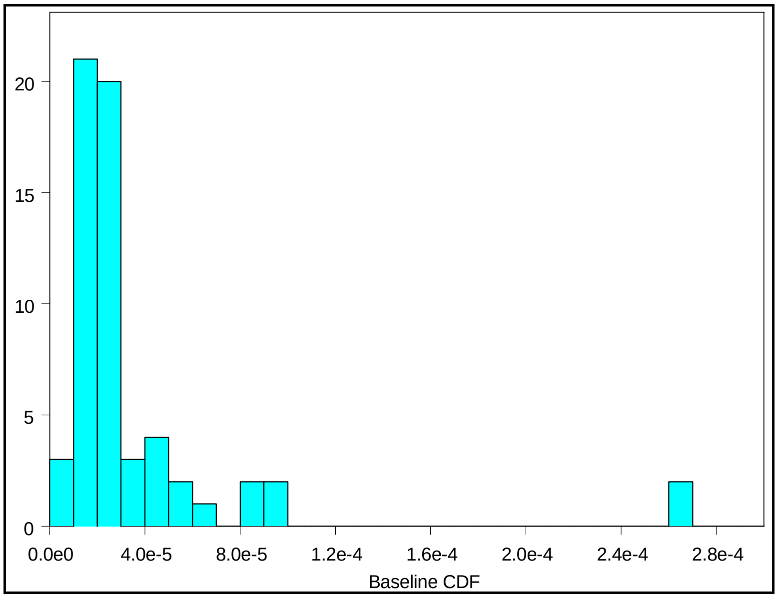

Figure E-13 Baseline CDF at 60 PWRs

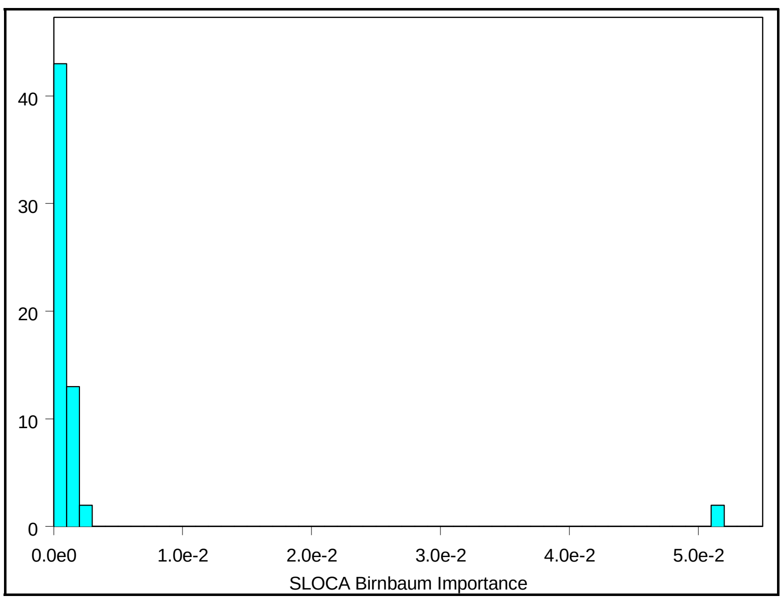

Figure E-14 Birnbaum importance of Small/Very Small LOCA at 60 PWRs

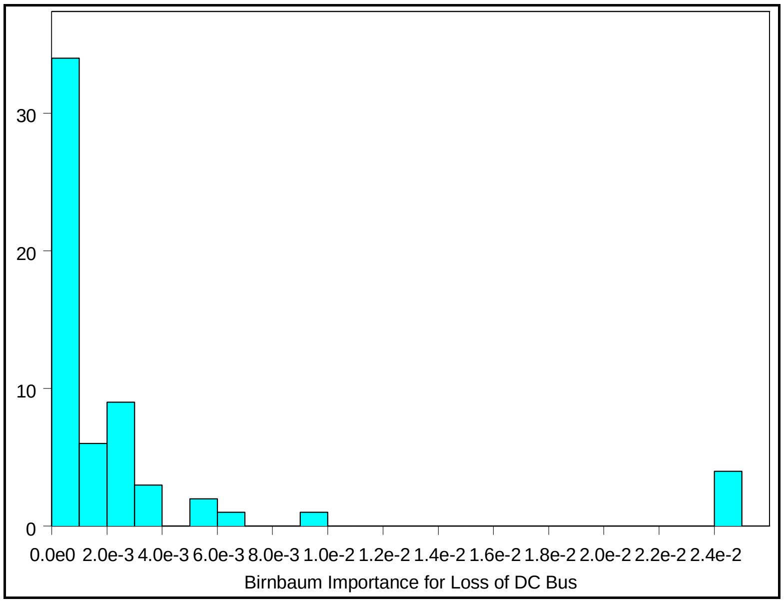

Figure E-15 Birnbaum importance of Loss of Vital DC Bus at 60 PWRs

E.5.3 Plant-Specific IIEI

Although this document deals with the IIIEI (CDF), it is possible to drop the “Industry” qualifier, and construct plant-specific Integrated Initiating Event Indicators (IIEIs). For this, we simply use the plant specific Birnbaum importances instead of the industry mean Birnbaum importances. Then the predictive distribution of each such indicator can be found. Figures E-16 and E-17 show these predictive distributions for the industry indicators and for selected extreme plants. Figure E-16 shows the predictive distribution of the IIIEI (CDF) for BWRs, and the IIEI (CDF) for the extreme plant in Figure E-11. In both cases, the indicator estimates the current initiating event frequencies by using the Bayes estimator with three years of data, as described in Section E.

The cumulative distribution for the industry mean corresponds to the density shown in Figure E-6. Figure E-6 and the industry portion of Figure E-16 are just two views of the same distribution, each showing that the distribution is concentrated for the most part between 5×10^{-6} and 2×10^{-5}. The distribution is shown as a histogram in Figure E-6, because a histogram is easily interpreted, and as a cumulative distribution in Figure E-16, because that figure shows more than one distribution simultaneously. The distribution shown in Figure E-16 for the one outlying plant is far to the right of the industry mean distribution. It contains a sequence of plateaus, with each new plateau corresponding to an additional occurrence of LOOP at some plant during the current three-year data window.

Similarly, Figure E-17 shows the predictive distributions of the integrated indicator for the PWR industry mean, and for selected individual plants. These are the plants with the largest baseline CDFs in Figure E-13.

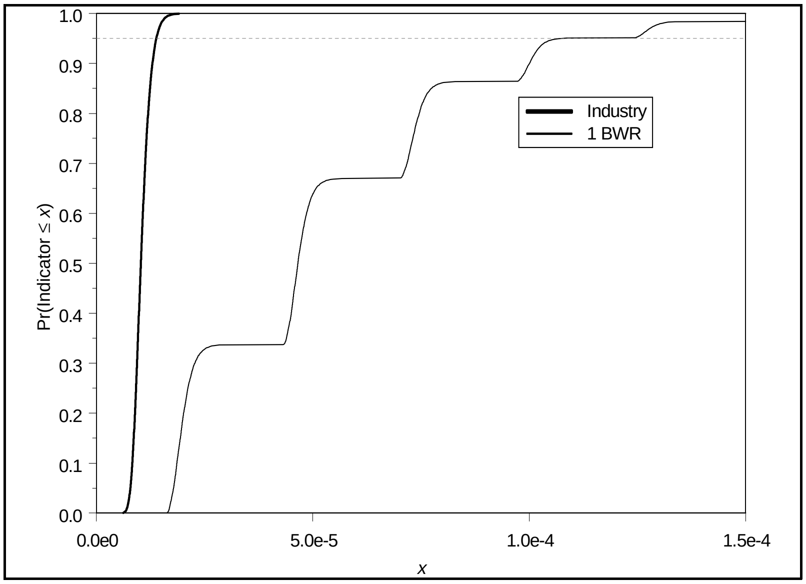

Figure E-16 Predictive cumulative distribution functions of Integrated Indicator, for BWR industry mean and for one outlying BWR

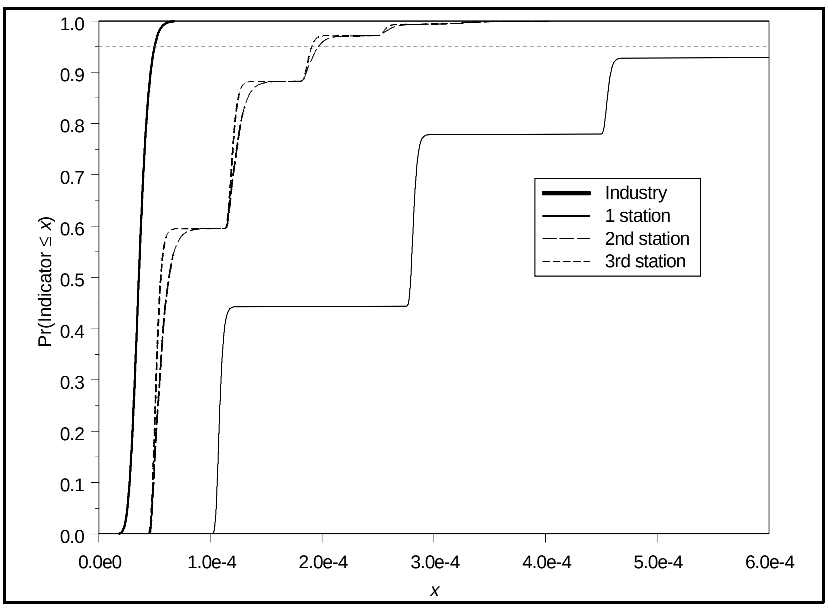

Figure E-17 Predictive cumulative distribution functions for integrated indicator, for PWR industry mean and for selected individual PWRs

E.6 REFERENCES

Atwood, Corwin L., 2002, *Predictive Distributions for Poisson and Binomial Counts*, STATWOOD 2002/1.1.

Atwood, Corwin L., 1996, "Constrained Noninformative Priors in Risk Assessment," *Reliability Engineering and System Safety*, Vol. 53, pp. 37-46.