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Monitoring and Reporting Industry Performance for the Initiating Events Cornerstone of Safety

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ABSTRACT

The U.S. Nuclear Regulatory Commission (NRC) Industry Trends Program (ITP) collects and analyzes industry-wide data, assesses the safety significance of results, and communicates results to Congress and other stakeholders. This report outlines potential enhancements in the ITP to comprehensively cover the Initiating Events Cornerstone of Safety. Future work will address other cornerstones of safety. The proposed Tier 1 activity involves collecting data on ten risk-significant initiating events, trending the results, and comparing yearly performance with prediction limits (allowable numbers of events, above which NRC action may occur). Details of the trending methodology and determination of prediction limits are presented in this report. Tier 1 results would be used by the NRC to monitor industry performance at the individual initiating event level. The proposed Tier 2 activity involves integrating the individual initiating event information into a single risk-based indicator, termed the Baseline Risk Index for Initiating Events or BRIIE. The BRIIE would be evaluated yearly and compared against a threshold. BRIIE results would be reported to Congress on a yearly basis. This report presents the details of the BRIIE development, its historical performance, simulated future performance, and uncertainty and sensitivity. Finally, potential NRC responses to Tier 1 and Tier 2 results are discussed.

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The U.S. Nuclear Regulatory Commission (NRC) provides oversight of plant safety performance on a plant-specific basis using both inspection findings and plant-level performance indicators as part of its Reactor Oversight Process (ROP). Individual issues that are identified as having generic safety significance are addressed using other NRC processes, including the generic communications process and the generic safety issue process. As discussed in SECY-01-0111, "Development of an Industry Trends Program [ITP] for Operating Power Reactors", the NRC's Office of Nuclear Reactor Regulation (NRR) initiated the ITP to complement these processes by monitoring and assessing industry-level trends in safety performance. The purposes of the ITP are to provide a means to confirm that the nuclear industry is maintaining the safety performance of operating reactors and, by clearly demonstrating that performance, to enhance stakeholder confidence in the efficacy of the NRC's processes. The objectives of the ITP are the following:

- 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 on the ROP.

- Assess the safety significance and causes of any statistically significant adverse industry trends, determine if the trends 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.

At present, the ITP is monitoring the performance of eight industry indicators developed by the former NRC Office of Analysis and Evaluation of Operational Data and trends identified by the Accident Sequence Precursor Program.

Potential Enhancements for Initiating Events Cornerstone of Safety

This report outlines proposed enhancements to the ITP to risk inform the trends for the Initiating Events Cornerstone of Safety. Specifically, two levels of activity are proposed. The lower level or Tier 1 activity involves trending risk-significant initiating events and monitoring yearly industry performance against prediction limits. The initiating events are listed in Table ES-1. Ten risk-significant initiating events are covered for pressurized water reactors (PWRs), while nine are covered for boiling water reactors (BWRs). Data for these initiating events -- numbers of events and corresponding reactor critical years -- are already being collected and analyzed by the NRC on a continual basis, so no additional data collection is needed to support the Tier 1 activity.

The prediction limits in Table ES-1 are performance based, and include both aleatory uncertainty (the randomness of the event count in the future year) and epistemic uncertainty (lack of perfect knowledge of the value of the baseline frequency). Both 95% and 99% limits are presented. An expert elicitation approach is proposed to decide which set of limits is most appropriate for the Tier 1 activity. For informational purposes, the actual industry performances for fiscal year (FY) 2002 are also shown in Table ES-1. None of the initiating event performances exceeded either set of limits.

Table ES-1 ITP Tier 1 performance-based prediction limits

Risk-significant Initiating Event	Baseline Mean Frequency (per Plant per Critical Year)	Reactor Critical Years Assumed for One Year of Industry Operation	Expected Number of Events Over One Year	95% Prediction Limit (Industry Event Counts Over One Year)	99% Prediction Limit (Industry Event Counts Over One Year)	Actual Industry Event Counts for FY 2002
PWR General Transients	7.64E-1	61.72	47	61	67	30
BWR General Transients	8.95E-1	31.77	28	39	44	22
PWR Loss of Heat Sink	9.74E-2	61.72	6	12	14	3
BWR Loss of Heat Sink	1.90E-1	31.77	6	12	14	6
Loss of Feedwater	1.02E-1	93.49	10	16	19	2
Loss of Offsite Power	1.71E-2	93.49	2	5	7	1
Loss of Vital AC Bus	2.75E-2	93.49	3	7	8	3
Loss of Vital DC Bus	2.96E-3	93.49	0.3	2	3	0
PWR Stuck Open SRV	3.12E-3	61.72	0.2	2	3	0
BWR Stuck Open SRV	2.13E-2	31.77	0.7	3	4	1
PWR Loss of Instrument Air	1.22E-2	61.72	0.8	3	5	1
BWR Loss of Instrument Air	1.08E-2	31.77	0.3	3	3	0
Small/Very Small LOCA	4.65E-3	93.49	0.4	3	4	0
PWR Steam Generator Tube Rupture	4.37E-3	61.72	0.3	2	3	0

As an example of the Tier 1 trending analysis, the historical performance of the PWR general transient is shown in Figure ES-1. Over the period FY 1988 through approximately FY 1997, industry performance improved considerably (the initiating event frequency dropped). However, over the period FY 1998 through FY 2001 (the period used for determining a baseline frequency), the industry performance was essentially constant. Including the FY 2002 initiating event data in the Tier 1 trending analysis did not produce any increasing trends. This is evident from Table ES-1, since the number of occurrences of any initiating event is well below its prediction limits.

These ITP Tier 1 activities will help the NRC identify degrading industry performance as an adjunct to the plant-specific performance assessment performed as part of the ROP. Potential NRC responses if one or more of the prediction limits are reached or exceeded are outlined in Section 2 of this report. Example scenarios are presented in Section 5 for illustrative purposes. Tier 1 activities and results are not reported to the U.S. Congress. However, the Tier 1 results will be placed on the NRC website for access by interested stakeholders.

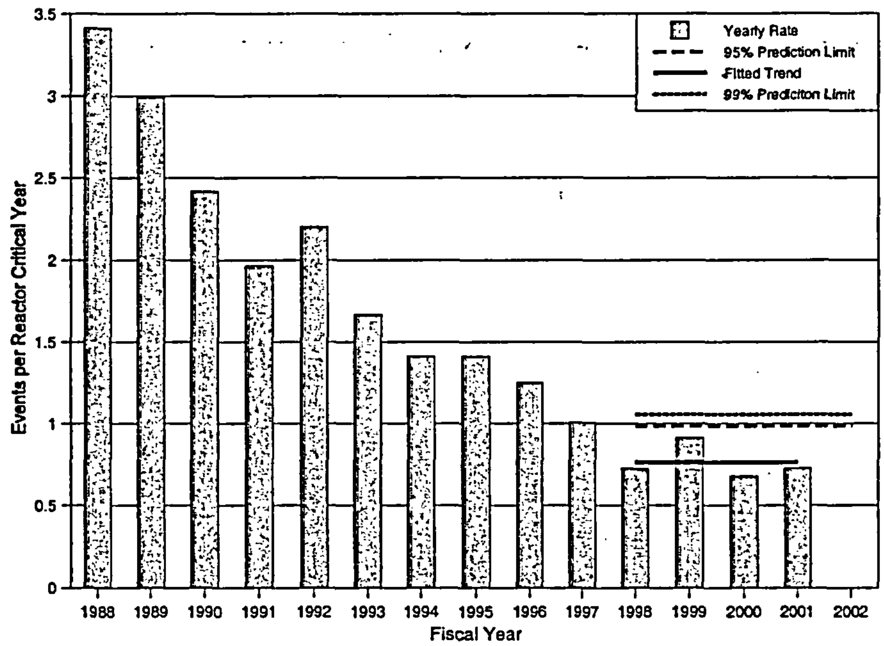

Figure ES-1 PWR general transient initiating event. The trend over the baseline period is not statistically significant (p-value = 0.625).

An integrated initiating events performance indicator is proposed for ITP Tier 2 coverage of the Initiating Events Cornerstone of Safety. It involves evaluating the risk significance of changes in industry initiating event performance (the results of the Tier 1 activity). Risk significance is evaluated in terms of changes in a measure related to core damage frequency, or ΔCDF. It combines operating experience for risk-significant initiating events with associated internal event CDF-based importance information. The indicator combines frequent and infrequent events with different risk measures (Birnbaum importances). This indicator is termed the Baseline Risk Index for Initiating Events, or BRIIE. Several different quantification methods were considered for evaluating the BRIIE. One method related to CDF is the following:

$$BRIIE = \sum_{i=1}^{m} \overline{B}_i \lambda^{*}_{ic},$$

where

$\overline{B}_i$ = industry - average Birnbaum for initiating event i (ES-1)

λ^{*}_{ic} = common industry current frequency for initiating event i

Another formulation, related to changes in CDF (ΔCDF), is given by the following equation:

$$BRIIE = \sum_{i=1}^{m} \overline{B}_i (\lambda_{ic}^{*} - \lambda_{ib}),$$

where

$$\overline{B}_i = \text{industry - average Birnbaum for initiating event i} \qquad \text{(ES-2)}$$

$$\lambda_{ic}^{*} = \text{common industry current frequency for initiating event i}$$

$$\lambda_{ib} = \text{baseline frequency for initiating event i}$$

BWRs and PWRs have different core damage frequencies, which depend to some extent on different initiating events. The risk weights for various initiating events are also different for the two types of reactors. Therefore, BRIIE results are proposed for each reactor type. However, the two BRIIE results could be combined into a single index, if desired. Historical performances of the PWR and BWR BRIIEs are presented in Figure ES-2.

Thresholds for the BRIIE

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

- Uncertainty in the BRIIEs 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 BRIIEs
- Sensitivity of BRIIEs 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.

Scope of the BRIIE

The PWR and BWR BRIIE indicators developed in this report are based on Birnbaum importance measures obtained from SPAR risk models. These models address only at power, internal event CDF. Shutdown and external events risks are not included. Only the initiating event frequencies vary; all other risk factors are held constant. Also, the relative importances of the various initiating events included in the BRIIE might change significantly if Birnbaum importances were to be determined based on the large, early release fraction (LERF) risk rather than CDF.

Implementation Steps

To implement the proposed ITP enhancements for the Initiating Events Cornerstone of Safety, several steps must be taken:

1. The staff can easily calculate the prediction limits for the Tier 1 individual initiating events, for any data window that may be of interest. This can be implemented very easily with little effort and cost.

2. Conduct a pilot exercise to set thresholds based on the current example calculations. From this we can learn what is the best way to present information to a panel and what additional information would be helpful when setting the thresholds.

3. The Birnbaum importance measures used to quantify the PWR and BWR BRIIEs were obtained from SPAR Rev. 3i and 3 models in the summer of 2002 for this demonstration exercise. Final Birnbaums should be obtained from the improved SPAR Rev. 3 models being completed by the NRC. The initiating event frequencies and the basic event failure probabilities should be updated before the final Birnbaum importance measures are estimated.
4. Perform studies using the SPAR models to provide information about the robustness of the BRIIEs. Compare with industry PRA models where possible.

5. Develop procedures, process, and quality assurance guides for the Tier 1 and Tier 2 activities.

6. The proposed Tier 1 and 2 activities should be formally incorporated into the ITP over a several-year period. This allows for refinements or enhancements as experience with these activities is accumulated.

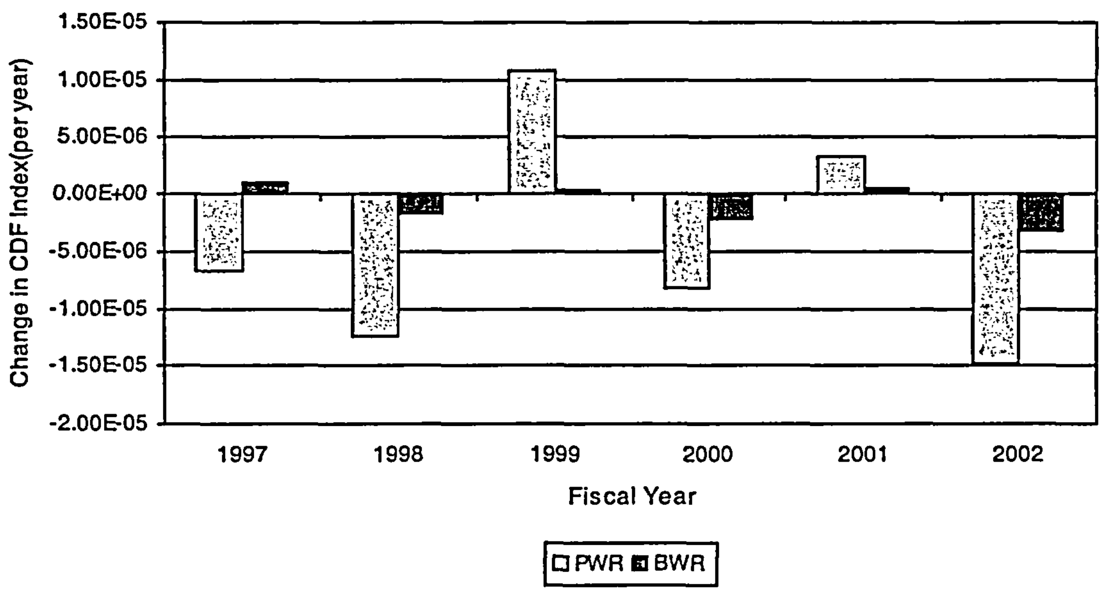

Figure ES-2 PWR and BWR BRIIE historical performance

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1 INTRODUCTION

1.1 Purpose of Report

Attachment 3 of SECY-03-57 (NRC 2003b) provides an overview of the develop of an integrated indicator for use in the Industry Trends Program (ITP) to cover the Initiating Events Cornerstone of Safety. The initial development was described in a draft report that was sent out for review and comment. The staff has given briefings on the integrated indicator concept during periodic ROP working group public meetings, and has briefed two subcommittees of the Advisory Committee on Reactor Safeguards (ACRS). In addition, a public workshop was held in July 2003. The staff has received valuable feedback during these meetings, and no major concerns have been identified to date. The staff intends to increase its interactions with stakeholders on the integrated initiating events indicator during this fiscal year, working towards a pilot program and possible implementation within 1–2 years.

This report incorporates feedback from the meetings. It clarifies concepts that were presented in the draft report, and it provides additional analyses to investigate the behavior of alternate ways of calculating the integrated indicator. Building on previous U.S. Nuclear Regulatory Commission (NRC) Office of Research (RES) work done to support improvements to the Reactor Oversight Process (ROP) [NUREG-1753, Hamzehee et al. 2002], the work reported here formulates proposed industry-level indicators and establishes their statistical properties and their risk significance. This report also identifies additional work that would be needed for implementation of the indicators.

The following subsections briefly present the elements of plant safety and performance and the key objectives of the ITP, and show how major features of the current approach reflect these key objectives. An overview of the logical flow of this report follows that presentation.

1.2 Nuclear Safety and Plant Performance

One of the NRC's strategic goals contained in its annual *Performance and Accountability Report,* NUREG-1542 (NRC 2002a), is to "prevent radiation-related deaths and illnesses, promote the common defense and security, and protect the environment in the use of civilian nuclear reactors." The NRC has five programs that focus on nuclear reactor safety–Licensing, License Renewal, Incident Response, Inspection and Performance Assessment, and Safety Research.

Performance assessment involves the collection, classification, and analysis of nuclear reactor performance data. Examples of such information include equipment failures and successes, descriptions of events that occur, power level, operating time, etc.

To obtain a complete picture of reactor performance, we must analyze and assess the information from three perspectives or dimensions. They are (1) individual events that occur at a plant, (2) individual plant performance, and (3) industry performance. These are shown pictorally in Figure 1. Each provides a perspective on safety performance. Focusing only on one or two of these areas does not provide a complete picture of reactor safety performance.

Individual Events

The NRC provides oversight of plant safety performance with respect to individual events by evaluations and inspections. The risk significance of individual events is evaluated in the Accident Sequence Precursor (ASP) Program. These events are ranked according to conditional core damage probability (CCDP). In addition, inspections are utilized to evaluate the events that are not readily amenable to risk evaluation and to obtain additional information and insights for feed-back to the industry and regulatory programs.

Individual Plant Performance

The NRC provides oversight of plant safety performance on a plant-specific basis using both inspection findings and plant-level performance as part of its ROP. Significant inspection findings are evaluated in the Significance Determination Process. Plant-specific risk analyses and probabilistic risk assessments also provide insights into individual plant performance.

Industry Performance

Industry performance is evaluated by the ITP. It provides insights that are not obtained by the other activities. For example, short-term increases in individual initiating event occurrences may not be revealed by the ROP, but the ITP would identify such performance. The increase in a yearly number of occurrences of an individual initiating event is also of interest. Emerging trends, as well as long-term trends, are also evaluated in the ITP.

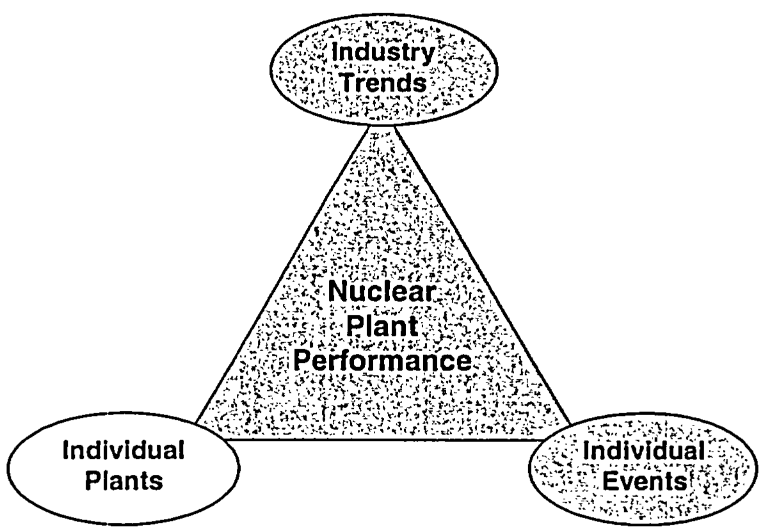

Figure 1 The three dimensions of performance

1.3 Objectives of the ITP

Annually, the NRC prepares the *Performance and Accountability Report,* NUREG-1542 (NRC 2002a), on a fiscal year (FY) basis for submittal to Congress. In this 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 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 2002d), was started to complement the ROP by monitoring and assessing industry-level safety performance. 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 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.

- 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 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 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 2002d)

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 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.

1.4 Relationship of the ITP and the ROP

The ITP complements the ROP in support of the NRC's "Maintain Safety" performance goal [NUREG-1614, NRC 2000a]. The ROP samples individual licensee performance through collection of performance data and through inspection. If performance is satisfactory, the NRC may simply continue to monitor performance; if performance at a plant is declining, the NRC response escalates as appropriate, based on the performance issues and their risk significance.

Most risk-significant issues developing at one or more plants will eventually manifest themselves through ROP mechanisms. However, for statistical reasons, some issues are difficult to identify through examination of individual plant performance; in such cases, the improved statistics resulting from aggregation of data at the industry level can help to identify issues earlier. This is part of what the ITP is intended to accomplish. In this respect, the ITP complements not only the ROP, but also other NRC programs, such as the generic communications and generic safety issues processes.

In addition to its role in maintaining safety, the ITP supports fulfillment of the NRC's responsibility to report industry trends in the annual *Performance and Accountability Report* to Congress, and other stakeholders, whether adverse trends in industry performance are developing, and what are their safety significance.

In keeping with the direction that was set in SECY 99-007 (NRC 1999a), the indicators discussed here are based on performance attributes that relate directly to risk (e.g., appear explicitly in quantitative risk models). As discussed in NUREG-1753, this priority leads to a selection of events whose risk significance makes them worth trending, and whose frequencies are such that significant changes in those frequencies can be determined within feasible observation times. With the subject events largely predetermined, the emphasis in the present development has been placed on the details of the mathematical formulation, demonstration of the statistical properties of the indicators in various performance scenarios, and clarification of the interpretations of the indicators' results.

1.5 Overview of the Concept

In order to support the diverse objectives identified above, a two-tiered approach to the ITP has been developed. Refer to Figure 2.

At the lowest level in Figure 2, the ROP (SECY 99-007) addresses performance at each individual plant. This is done based on a comprehensive program of inspections and on evaluation of multiple performance indicators. These indicators are highly sensitive; their thresholds are set in such a way that the agency responds even to very small changes in risk, changes that are insignificant fractions of the estimated risk. This is in accord with NRC's position that thresholds are to be set such that even if a threshold is crossed as a result of a performance issue, there remains substantial margin before a serious safety problem exists. Specific information is analyzed in specific ways to support the ROP. NRC response to indicators and inspection findings is given in the ROP's "Action Matrix."

The ITP operates at higher levels of aggregation, as shown in Figure 2. At Tier 1, information is provided at the industry level about specific initiating event frequencies. At this level, plant-specific data are aggregated and industry trends are estimated for specific initiating events, in order to determine whether adverse trends exist. This is used to complement the ROP by assessing industry performance. The ITP identifies issues that affect multiple plants and multiple sites. These industry indicators are monitored using "prediction limits" and statistical trending tools. Such indicators include the current industry performance indicators originally developed by the former AEOD, initiating event trends, or trends in the ROP indicators.

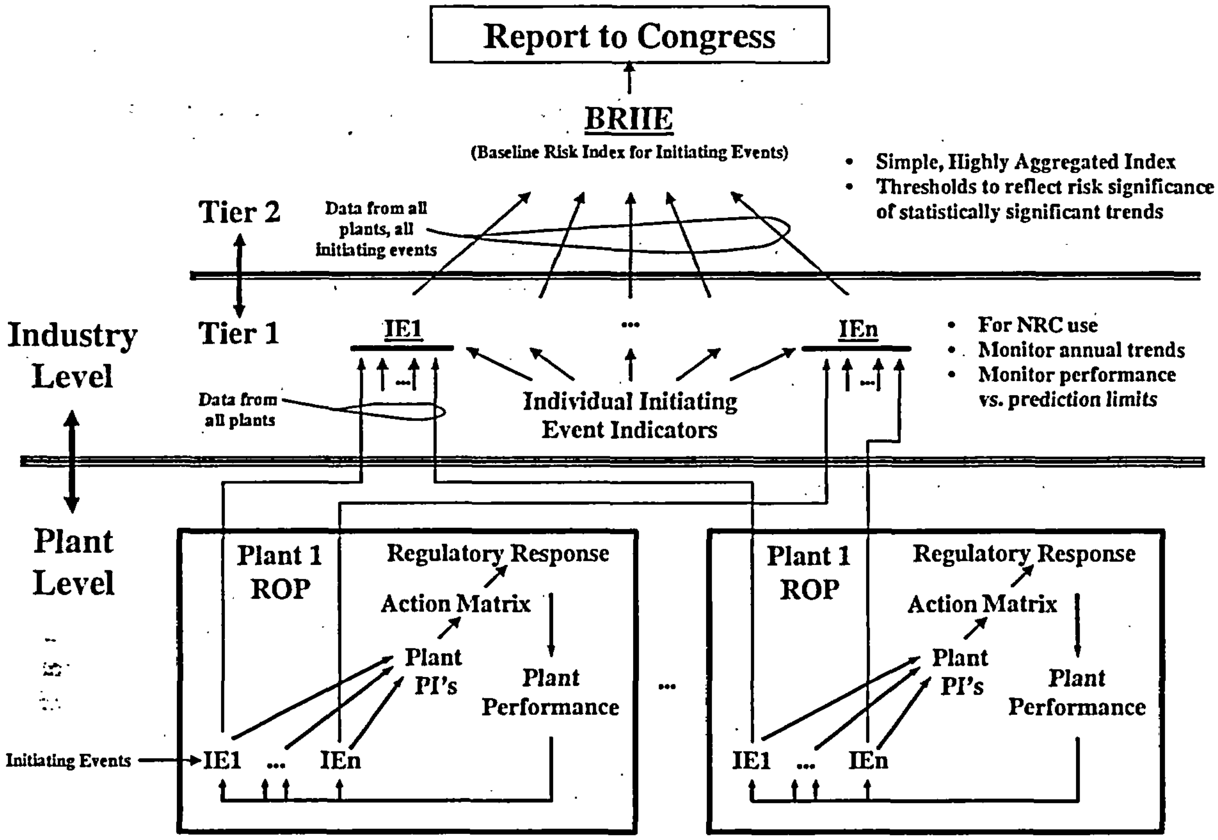

Figure 2 Relationship of the Reactor Oversight Process and the Industry Trends Program

Finally, at the top level, denoted as Tier 2 in Figure 2, another function of the ITP is identified – that of providing input for the NRC annual *Performance and Accountability Report* to Congress. At this level, information is even more aggregated. This is done because there are many indicators at the Tier 1 level, too many to be used for a report to Congress. The indicator to be reported to Congress and other stakeholders needs to be as simple and unambiguous as possible. The intended function of this indicator can be compared to that of a warning light on an automobile dashboard. Illumination of such a warning light signals the presence of an underlying condition that needs attention, without itself providing diagnostic detail. This function is accomplished for the initiating events cornerstone by aggregating individual indicators, such as initiating event types, into a single indicator for this application. Periodic maintenance, monitoring of the individual Tier 1 indicators, can reduce the chance of this warning light illuminating.

The Tier 2 indicator is called the "Baseline Risk Index for Initiating Events (BRIIE)." While still relating to risk significance, the BRIIE's threshold has a very different intent from the thresholds used in the ROP indicators. The BRIIE's threshold needs to be determined based on a mix of policy and technical considerations, including a careful statement of the proper interpretation to be attached to the annual report to Congress. A process for determination of this threshold will be discussed later in this report.

In summary, Figure 2 shows two "tiers" of industry-level performance indicators at different levels of aggregation, and relates these indicators to the more detailed information developed under the ROP. Several distinct mechanisms operate to identify emerging performance issues. The Tier 2 indicator can be compared to a warning light on an automobile dashboard. Illumination of such a warning light signals the presence of an underlying condition that might have been detected and addressed earlier by other means.

As suggested by Figure 2, several other means are available to identify emerging performance issues. One such means is licensee corrective action processes, and another is the ROP. In addition to these mechanisms, significant operating events are analyzed by the NRC, both as part of plant-specific oversight and as part of the NRC's program to derive generic insights from operating experience. Finally, Tier 1 of the ITP aggregates industry-level performance data in specific functional areas, looking for trends that would not be manifest in plant-specific data.

1.6 Overview of this Report

Section 2, immediately following this introduction, expands on the above summary of the ITP's objectives and structure. Following that, Section 3 presents a detailed development of the Tier 1 indicators, including their statistical properties and recommendations for their thresholds. Section 4 presents a comparable development of the BRIIE. Potential examples and corresponding NRC response to these indicators are discussed in Section 5, including an example based on the August 14, 2003 grid event. Finally, Section 6 summarizes insights, recommendations, and outlines steps necessary for implementation. Appendix A contains additional information about regarding the uncertainty analysis of the BRIIE. Appendix B presents information about the initiating event Birnbaum importances..

2. ITP PROCESS AND THE BRIIE

2.1 Introduction

The ITP process is described in Attachment 1 to SECY-03-0057 (NRC, 2003b). The attachment contains a flowchart of the process. The flowchart shows the two activities of the ITP – monitoring industry performance (represented by the dashed line) and providing input to the annual *Performance and Accountability Report* to Congress (represented by the solid line). Figure 3 has been tailored to the ITP process with respect to the initiating events cornerstone.

The steps for the ITP monitoring activity are data collection, identification of short-term issues, analysis of issues, and agency response. Reports are provided to senior NRC management, stakeholders and the Commission. (This is the Tier 1 in Figure 2.)

The steps for the long-term trend are data collection, identification of adverse trends, analyses of issues, agency response, senior management review, communications, and finally the annual *Performance and Accountability Report*. (This is the Tier 2 in Figure 2.)

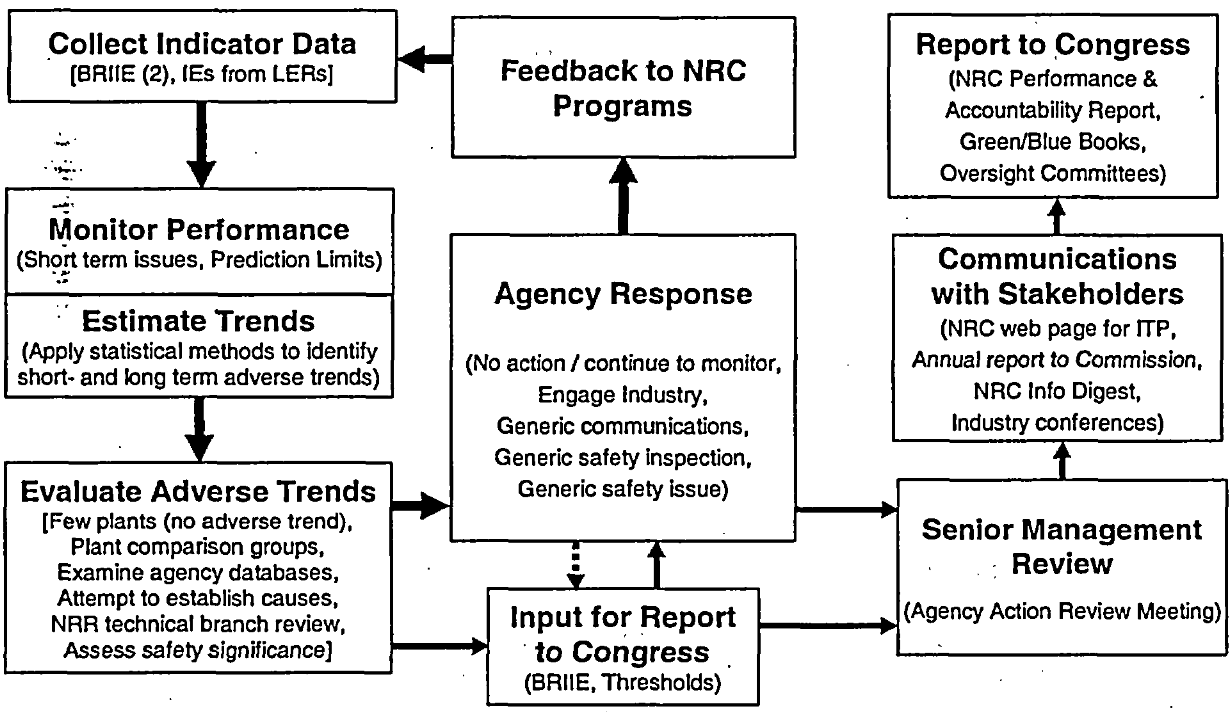

Figure 3 BRIIE and the ITP process

2.2 Monitoring Industry Performance (Tier 1)

Figure 3 outlines the ITP Tier 1 monitoring activity. This activity includes the loop indicated by the heavy black line. It starts with "Collect Indicator Data" and ends with "Feedback to NRC Programs." Also included is "Communications with Stakeholders."

Data for the trends being considered in the ITP come from data already provided to the NRC by industry. These sources include the existing ROP performance indicator data, licensee event reports (LERs), and also the Equipment Performance Information eXchange System (EPIX) maintained by the Institute of Nuclear Power Operations (INPO). No additional information is required from licensees. NRC bins and categorizes the data by the appropriate cornerstone of safety. For the initiating events discussed in this report, the ITP uses information from LERs.

The ITP monitors or evaluates industry performance in two ways. The first way deals with assessing whether an unusually large number of events have occurred in the last year. The second way deals with determining whether an adverse trend exists or is starting. This trending analysis requires at least four years of data.

Once the data are collected and properly binned, the staff evaluates the annual performance for the individual initiating events using predictive distributions and compares the observed number of events with "prediction limits" to provide a consistent method to identify potential short-term emergent issues before they manifest themselves as long-term trends.

For purposes of assessing whether there are any statistically significant adverse industry trends, only long-term data are used. Trending long-term data minimizes reacting to potential "false positive" indications that may emerge in short-term data. "Long term" was defined to be four or more years to ensure that sufficient data (i.e., data for at least two typical nuclear plant operating cycles) is available so that valid trends can be distinguished from operating cycle effects such as refueling outages and from random fluctuations in the data and to allow sufficient data for the use of statistical methods. As stated in the ITP Commission papers, a seeming "positive" indication of an adverse trend at this level needs to be evaluated in light of the following:

- The magnitude of the trend – how risk-significant the trend is
- The persistence of the trend – how long the trend has been going on
- The pervasiveness of the trend – how many plants are affected by the underlying influences causing the trend
- What agency effort has been applied to reverse the trend, and how effective this agency effort has been.

Once an adverse trend is identified, the staff conducts an initial analysis of information readily available in the databases used to compile the indicator data to determine whether the trend is unduly influenced by a small number of outliers and to identify any contributing factors. If the trend is the result of outlying plants, then it is not considered a trend requiring generic actions, and the agency will consider any appropriate plant-specific actions using the ROP. For example, the affected plants unduly influencing the adverse trend may have already exceeded plant-level thresholds under the ROP, and the NRC regional offices would conduct supplemental inspections at these plants to ensure the appropriate corrective actions have been taken. If the plants did not exceed any thresholds, while the NRC would not take regulatory actions beyond the ROP, the NRC would gather additional information on the issue within the scope of the ROP using risk-informed baseline inspections. The results of these inspections would be examined to determine if a generic issue existed requiring additional NRC review or generic inspections.

If no outliers are identified, the staff conducts a broader review to assess whether larger groups of facilities are contributing to the decline and to assess any contributing factors and causes. For example, the data review is expanded to include a review of various plant comparison groups, contributing factors such as the operational cycle stage of the facilities (shutdown, at-power, startup from refueling, etc.), and the apparent causes for the data (equipment failures, procedure problems, etc.). The staff will also conduct a more detailed review of applicable LERs. Should a group of plants be identified, the staff will examine the results of previously conducted inspections at these plants, including any root causes and the extent of the conditions.

Once this information is reviewed, the staff assesses the safety significance of the underlying issues. The staff is mindful that trends in individual indicators must be considered in the larger context of their overall risk significance. For example, a hypothetical increase in automatic scrams from 0.4 to 0.7 per plant per year over several years may be a statistically significant trend in an adverse direction. However, it may not represent a significant increase in overall risk since the contribution of a small number of scrams is relatively low, and it is possible that overall risk may actually have declined if there were reductions in the frequency of more risk-significant initiating events or if the reliability and availability of safety systems had improved. Depending on the issues, the staff may perform an additional evaluation using the most current risk analysis tools or an evaluation by the ASP Program.

Should a statistically significant adverse trend in safety performance be identified or an indicator cross a prediction limit, the staff will determine the appropriate response using the NRC's established processes for addressing and communicating generic issues. These processes are described in SECY-99-143, "Revisions to Generic Communications Program" (NRC 1999b).

In general, the issues will be assigned to the appropriate branch of NRR for initial review. The branch will engage NRC senior management and initiate early interaction with the nuclear power industry. Depending on the issue, the process could include requesting industry groups such as the Nuclear Energy Institute (NEI) or various owners groups to provide utility information. As discussed in SECY-00-0116, "Industry Initiatives in the Regulatory Process" (NRC 2000b) industry initiatives, such as the formation of specialized working groups to address technical issues, may be used in lieu of, or to complement, regulatory actions. This can benefit both the NRC and the industry by identifying mutually satisfactory resolution approaches and reducing resource burdens.

Depending on the issues, the NRC may consider generic safety inspections at plants. In addition, the issues underlying the adverse trend may also be addressed as part of the generic safety issue process by RES. After this interaction, the NRC may consider additional regulatory actions as appropriate, such as issuing generic correspondence to disseminate or gather information, or conducting special inspections for generic issues. The process also includes consideration of whether any actions proposed by the NRC to address the issues constitute a backfit.

Two kinds of feedback to regulatory programs may result from the ITP: insight into the effectiveness of the ROP, and indication of emerging generic issues. Identification of an adverse trend at the industry level would suggest that some influence common to multiple plants is operating. One influence that all U.S. plants have in common is that they are subject to the same ROP. Thus, the ITP has the potential to provide an oversight activity for the ROP. Adverse trends in prevention of specific initiating events at multiple plants will focus attention not only on licensee controls at those plants, but also potentially on the effectiveness of regulatory oversight of those areas.

Another potential feedback to regulatory programs is identification of generic safety issues related to such factors as plant aging, or changes in the plants' external operating environments (e.g., changes in the condition of the grid).

Finally, the NRC communicates overall industry performance to stakeholders by publishing the ITP indicators on the Nuclear Reactors portion of the agency's public web site at *http://www.nrc.gov/reactors/operating/oversight/industry-trends.html.* The staff believes that communication of the industry-level indicators, when added to the information on individual plants from the ROP, enhances stakeholder confidence in the efficacy of the NRC's oversight of the nuclear industry.

The staff informs the NRC Commission of the results of the ITP in an annual report in the same time frame as the Annual Agency Review Meeting (AARM). The indicators are also published annually in the NRC's "Information Digest 200X" (NUREG-1350 series, NRC 2002c). In addition, NRC managers have also historically presented industry indicators and trends at major conferences with industry.

2.3 Reporting to Congress (Tier 2)

The Government Performance and Results Act of 1993 (OMB 1993) requires all federal government agencies to develop agency performance goals and agency performance measures and report them to Congress. The NRC prepares its *Performance and Accountability Report* (NUREG-1542, NRC 2002a) on a fiscal year basis for submittal to Congress. This report presents the agency's success in meeting its annual performance goals, its important accomplishments, the actions it has taken to address management challenges, and its financial condition during the past fiscal year. The report gives the agency's stakeholders an opportunity to assess how the agency serves the American public and how it manages the funds entrusted to it.

One major purpose of the ITP is to support this specific reporting requirement. An output of the ITP is that it provides agency monitoring and reporting in the Nuclear Reactor Safety arena against the current performance goal measure of "no statistically significant adverse industry trends in safety performance," as defined by the NRC's Strategic Plan. The agency reports these results annually to Congress in the *Performance and Accountability Report*, Fiscal Year 200X" (NUREG-1542 series). The current bases for assessing performance against this measure are trends in the industry indicators developed by the former AEOD and trends identified by the ASP Program.

Figure 3 outlines the ITP Tier 2 activity. This activity includes the flow starting with "Input for Report to Congress" and ending with "Report to Congress." Given the data collected and quantified in Tier 1, an integrated, risk-based index (the BRIIE) can be constructed as a single high-level measure of industry initiating event performance. Development of the BRIIE and its thresholds is discussed in Section 4 of this report. Thresholds for the BRIIE will be determined by a panel. The thresholds will consider risk significance, statistical significance, and other considerations.

The industry trends program, results, and agency response are reviewed annually during the AARM. In general, the AARM is intended to review the appropriateness and effectiveness of staff actions already taken, rather than to make decisions on agency actions. NRC senior managers from headquarters and the regions review the industry trends information and, if appropriate, recommend any additional actions beyond those implemented by the staff. The staff informs the Commission of the status of the industry via the ITP annual Commission paper.

The NRC reports the industry indicators to Congress annually in the NRC's "*Performance and Accountability Report*, Fiscal Year 200X" (NUREG-1542 series), and in the NRC's "Budget Estimates and Performance Plan Fiscal Year 200X" (NUREG-1100 series, NRC 2003). The indicators demonstrate how the agency has met the measure of "no statistically significant adverse industry trends in safety performance" for the performance goal of maintain safety. Adverse trends would be reported, but indicators that exceeded prediction limits need not be included in these reports since these are tools to monitor industry performance rather than desired thresholds of performance. In addition, the Commission has historically used the ITP indicators when presenting the status of industry performance to the NRC's oversight committees.

As noted earlier, all indicators – not just the BRIIE – will be publicly available: ROP indicators, ITP Tier 1 indicators, and ITP Tier 2 indexes (BRIIE plus possible future indicators). When indications in all areas are simultaneously improving, communication with stakeholders is straightforward. When such is not the case, some additional information (discussion, interpretation) may need to be supplied. If some Tier 1 frequencies are increasing slightly but the increase is not statistically meaningful or has only persisted for a short time, the reason this is not a "statistically significant adverse trend" may need to be explained. If increases in some areas are offset by apparent decreases in other areas, then this, too, may need to be explained. Finally, it is important to keep perspective on the objectively small magnitudes of the changes in risk being analyzed within this program.

3. MONITORING INDUSTRY PERFORMANCE FOR INDIVIDUAL INITIATING EVENTS (TIER 1)

3.1 Introduction

ITP Tier 1 coverage of the Initiating Events Cornerstone of Safety involves trending risk-significant initiating events and monitoring yearly industry performance against prediction limits. These ITP Tier 1 activities help the NRC identify degrading industry performance such that appropriate NRC actions can be taken.

3.2 Risk-significant Initiating Events Covered

The initiating event study (Poloski et al. 1999) provides data for a large number of initiating event types for the period calendar year (CY) 1987 through CY 1995. Initiating events are defined in that study to be unplanned reactor trips that occur while a plant is critical and at or above the point of adding heat. A subset of these events has been identified as being risk significant (Hamzehee et al. 2002). The list of risk-significant initiating events considered in the ITP is presented in Table 1. This list includes ten initiating events applicable to PWRs and nine applicable to BWRs. Initiating events broken down into separate PWR and BWR categories were shown to have statistically significant differences in frequencies in the initiating events study. For the other initiating events, PWR and BWR frequencies were not significantly different, and both types of reactors were combined to obtain frequencies. In general, these risk-significant initiating events cover approximately 90% of the internal event core damage risk (excluding internal flooding) from the 103 operating commercial nuclear power plants in the U.S.

For comparison purposes, the ROP monitors three performance indicators under the initiating events cornerstone: unplanned scrams, scrams with loss of normal heat removal, and unplanned power changes. The ROP counts all unplanned scrams and does not distinguish the risk significance of various types of unplanned scrams. The ROP unplanned scrams is defined as number of events per 7000 reactor critical hours.

In contrast, the ITP initiating events are categorized by their risk significance and functional impact on the plant as presented in Table 1. Scrams resulting in these specific functional impacts are covered under separate, risk-significant initiating events. Thus, scrams are binned as loss of feedwater, loss of offsite power, loss of vital DC bus, general transients, etc. The ITP general transients category includes only those unplanned trips that do not result in specific functional impacts such as loss of heat sink, loss of offsite power, etc. The ROP unplanned scrams indicator is similar to the ITP general transients initiating event. However, for a given year of industry operation, the total number of events in the ROP unplanned scram indicator will be larger (10 to 20%) than the number of events included in the ITP general transient initiator.

The ROP scrams with loss of normal heat removal indicator includes events that are subdivided into two initiators in the ITP: loss of heat sink and loss of feedwater. Again, the two programs differ in terms of the quantitative definition of the indicator. The ROP counts three years of events, while the ITP is number of events (plus 0.5) divided by number of reactor critical years (any interval could be chosen).

Finally, the ROP unplanned power changes performance indicator does not involve scrams. Also, this indicator cannot be easily related to impacts on CDF. Therefore, this indicator has no comparable event in the ITP risk-significant initiating event list.

The three ITP risk-significant initiating events that roughly correspond with ROP performance indicators occur frequently enough such that they can be monitored on a plant-specific basis over a period of one or three years. However, their coverage of internal events core damage risk ranges from 10 to 30%. The ITP includes the other risk-significant initiating events listed in Table 1 because of two reasons: including these other events increases the risk coverage to approximately 90%, and these events are frequent enough to monitor on an industry-wide basis.

Table 1 ITP risk-significant initiating events

ITP Risk-Significant Initiating Event	PWR	BWR	Combined	Comparable ROP Initiating Event Performance Indicator
General Transient	X	X		Unplanned Scrams
Loss of Heat Sink	X	X		Scrams with Loss of Normal Heat Removal
Loss of Feedwater			X	Scrams with Loss of Normal Heat Removal
Loss of Offsite Power			X	Counted under the unplanned scrams indicator. However, the functional and risk impacts on the plant are not covered. Also, this event is too rare to monitor separately on a plant-specific basis.
Loss of Vital AC Bus			X	Same comment
Loss of Vital DC Bus			X	Same comment
Stuck Open SRV	X	X		Same comment
Loss of Instrument Air	X	X		Same comment
Small/Very Small LOCA			X	Same comment
Steam Generator Tube Rupture	X	N/A		Same comment

3.3 Historical Performance

The historical performances of the ITP risk-significant initiating events are presented in Figures 4 through 17 for the period FY 1988 through FY 2001. The more frequent events such as general transient, loss of heat sink, and loss of feedwater show significant drops in frequencies (performance improvement) over time. Also, less frequent events such as loss of offsite power and loss of instrument air show significant decline through FY 2001. Finally, the other initiating events generally have too few events to judge whether performance is improving or degrading.

3.4 Baseline Period and Frequency

For each initiating event considered, a baseline period must be established. The baseline period is used to determine a baseline frequency for the initiating event. Also, the baseline period data are then used as input to the predictive limits analysis. Baseline periods for ITP risk-significant initiating events are listed in Table 2 and shown in Figures 4 through 17.

To guide the determination of the baseline period, the following characteristics were identified:

- The baseline period is representative of current industry performance.
- 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.

Because of the second 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, FY 1988. Candidate baseline periods were considered, starting in any year from the earliest year to FY 1998 and ending in FY 2001. (Because of the requirement for at least four years of data, FY 1998 is the latest starting year allowed, given data through FY 2001.)

For each candidate baseline period, a trend model was fitted to the data (Atwood 1995). Any trending model assumes a distributional form, such as independent Poisson counts in time. The observable quantity X_i, which is the event count for a specific initiating event in year 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 modeled as $\exp(a + b \times i)$, or equivalently, $\ln(\lambda) = a + b \times i$. The subscript i indexes the years in the data set, with i=1 for the first year, i=2 for the second year, etc.

To address the third bulleted item, the p-value for testing the no-trend model was calculated. In the present setting the p-value is as follows. We wish to investigate whether there is really a trend or not. The data produce an estimate of b that is not zero, at least not exactly, but this might occur even if λ is constant. So we ask, "What is the probability that Poisson data with constant λ would produce an estimate of b as large in absolute value as we saw?" This probability is the p-value. It measures how far the data are from constant. If the p-value is small, such as < 0.05, then there is strong ("statistically significant") statistical evidence that λ is not constant. If the p-value is large, there is little or no evidence against constant λ.

In this way, each candidate starting year was assigned a corresponding p-value, measuring the constancy of λ from the starting year through FY 2001. 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.

Baseline performance results for the risk-significant initiating events are summarized in Table 2. The baseline mean frequencies in Table 2 were obtained by updating a Jeffreys prior with the experience from the baseline periods as chosen above. With this prior, the posterior mean frequency is equal to (baseline period number of events + 0.5) / (baseline period reactor critical years).

3.5 Prediction Limits

Predictive distributions for the risk-significant initiating events are required for two purposes: establishment of prediction limits, and simulation of the integrated index discussed in Section 4. The prediction limits are performance-based (not risk-based) limits derived from past industry performance over the baseline periods discussed in Section 3.4.

For events in time 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 has probability mass function:

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

where

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

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

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

Two possible prediction limits are calculated using Equation (2): 95% and 99% prediction limits on the future count. That is, the prediction limit $x_{0.95}$ is the smallest number such that $\Pr(X \geq x_{0.95}) \leq 0.05$. The prediction limit $x_{0.99}$ is the smallest number such that $\Pr(X \geq x_{0.99}) \leq 0.01$. The final choice of which prediction limit to use, 95% or 99%, will be made by a panel.

Prediction limits for the ITP risk-significant initiating events are presented in Table 2. As an example of how to interpret the information in Table 2, consider the PWR general transient initiating event. Figure 4 shows the historical performance of this initiator over the period FY 1988 through FY 2001. Industry performance has improved considerably over this period. To obtain a current estimate of baseline performance (using the guidelines discussed in Section 3.4), the baseline period chosen is FY 1988 through FY 2001. Over this baseline period, the baseline frequency is 0.764/reactor critical year, based on 182 events and 238.97 reactor critical years. For purposes of predicting event counts for future years (FY 2002 and on), it is assumed that the 69 PWRs in the U.S. will contribute 61.72 reactor critical years during each FY, which represents approximately 90% critical operation for the PWR group. (The 61.72 reactor critical years was the actual performance of the 69 PWRs during FY 2001.) For future years, the expected number of general transients is (0.764/reactor critical year)(61.72 reactor critical years) = 47/year. In contrast, the 95% prediction limit is 61 events, and the 99% prediction limit is 67 events. These limits are based on historical performance and are not explicitly related to risk. However, risk-based limits, similar to those discussed in Section 4, could be generated for each individual initiating event if desired.

The prediction limit includes both aleatory uncertainty (the randomness of the event count in the future year) and epistemic uncertainty (lack of perfect knowledge of the value of the baseline frequency). As an example, consider again PWR general transients. For any λ, the number of events, X, in time t is distributed Poisson (λt). When t is set to 61.72 reactor-critical-years and λ is set to the baseline mean of 0.764/reactor critical year, then $\Pr(X \geq 61 \mid \lambda t) = 0.030$, which is less than 0.05. However, λ is not known exactly. Instead, it is estimated from the baseline data, covering four years for PWR general transients. Starting with the Jeffreys noninformative prior, gamma(0.5, 0), and updating it with the baseline data (182 events in 238.97 reactor-critical-years), we obtain that the baseline distribution of λ is gamma(182.5, 238.97). Denote this probability density function by $g(\lambda)$. Then the predictive probability of 61 or more events is

$$\Pr(X \geq 61) = \int \Pr(X \geq 61 | \lambda t) g(\lambda) d\lambda \ .$$

This is a weighted average of the probabilities, weighted by the probability of λ. This number is 0.047, which is less than 0.05. The same calculation using 60 instead of 61 events gives a probability > 0.05. Therefore, 61 is the 95% prediction limit.

Also presented in Table 2 are the actual industry event counts for FY 2002. None of the initiating event counts lie above the 95% or 99% prediction limits.

Table 2 Baseline periods, frequencies, and prediction limits

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)	Actual Industry Event Counts for FY 2002
PWR General Transients	1998	7.64E-1	238.97	182	61.72	61	67	30
BWR General Transients	1997	8.95E-1	146.89	131	31.77	39	44	22
PWR Loss of Heat Sink	1991	9.74E-2	641.91	62	61.72	12	14	3
BWR Loss of Heat Sink	1996	1.90E-1	176.21	33	31.77	12	14	6
Loss of Feedwater	1993	1.02E-1	785.43	80	93.49	16	19	2
Loss of Offsite Power	1997	1.71E-2	439.36	7	93.49	5	7	1
Loss of Vital AC Bus	1988	2.75E-2	1182.26	32	93.49	7	8	3
Loss of Vital DC Bus	1988	2.96E-3	1182.26	3	93.49	2	3	0
PWR Stuck Open SRV	1988	3.12E-3	800.62	2	61.72	2	3	0
BWR Stuck Open SRV	1993	2.13E-2	258.18	5	31.77	3	4	1
PWR Loss of Instrument Air	1990	1.22E-2	696.11	8	61.72	3	5	1
BWR Loss of Instrument Air	1994	1.08E-2	231.51	2	31.77	3	3	0
Small/Very Small LOCA	1988	4.65E-3	1182.26	5	93.49	3	4	0
PWR Steam Generator Tube Rupture	1988	4.37E-3	800.62	3	61.72	2	3	0

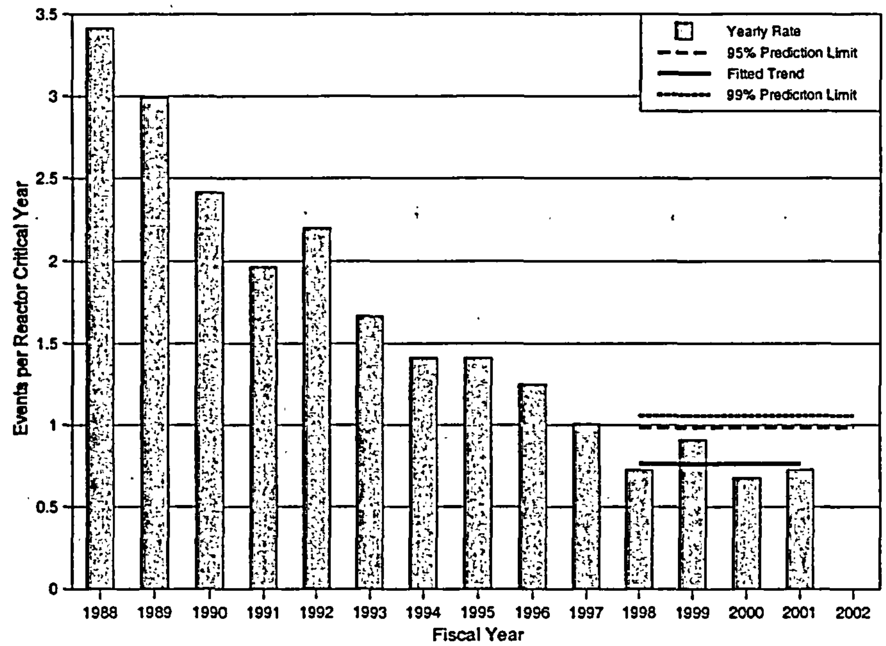

Figure 4 PWR general transient initiating event. The trend over the baseline period is not statistically significant (p-value = 0.625).

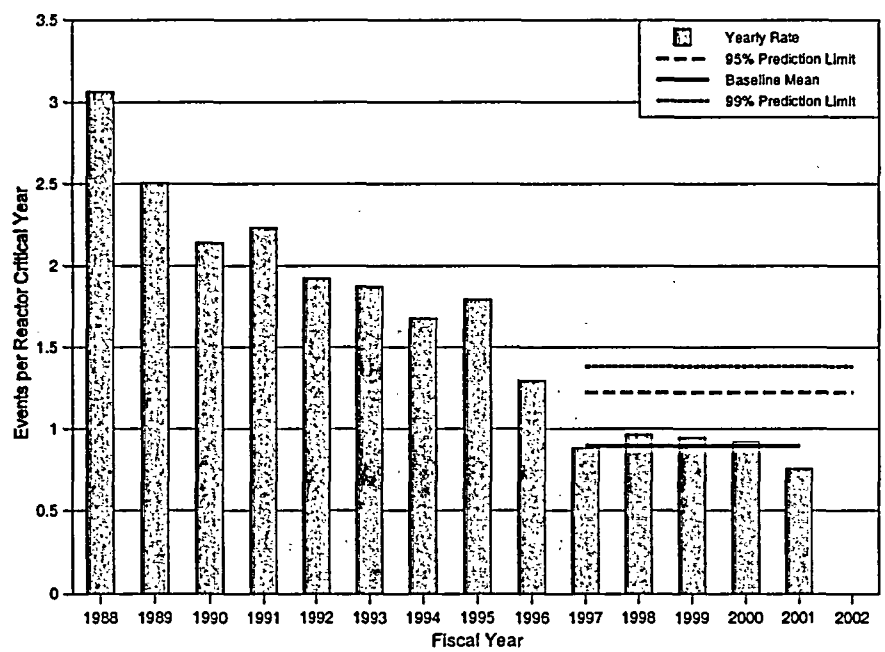

Figure 5 BWR general transients initiating events. The trend over the baseline period is not statistically significant (p-value = 0.566).

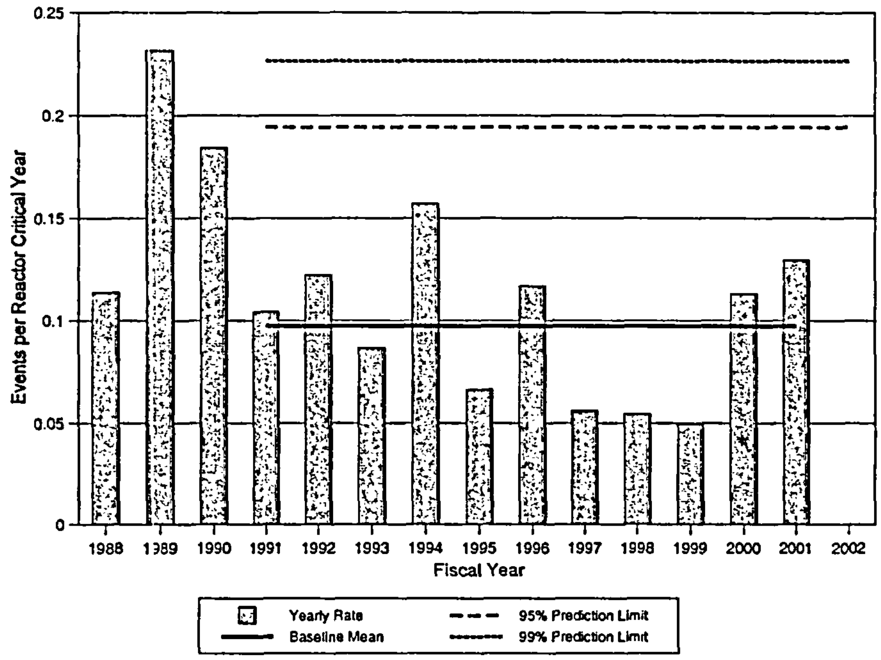

Figure 6 PWR loss of heat sink. The trend over the baseline period is not statistically significant (p-value = 0.614).

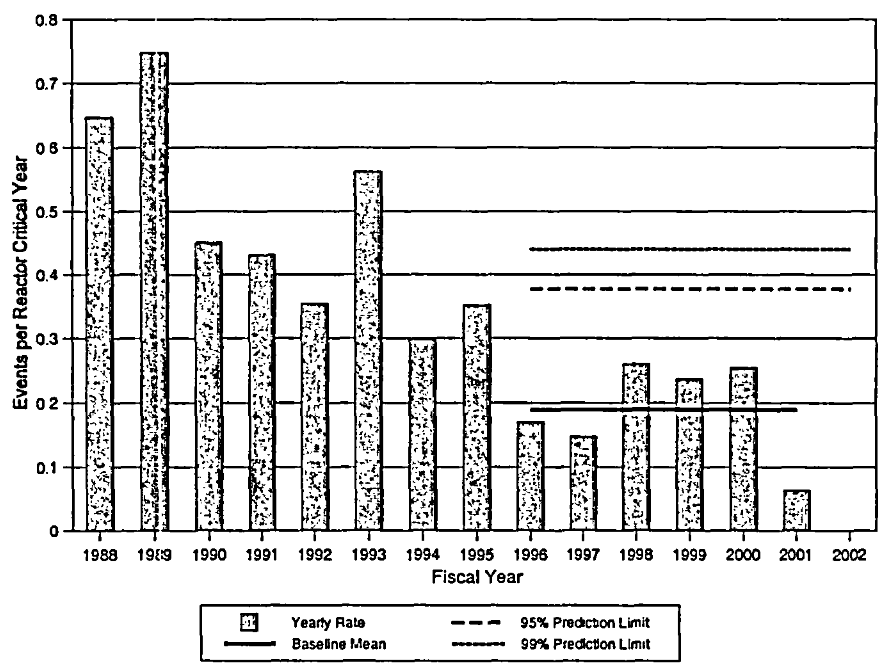

Figure 7 BWR loss of heat sink. The trend over the baseline period is not statistically significant (p-value = 0.874).

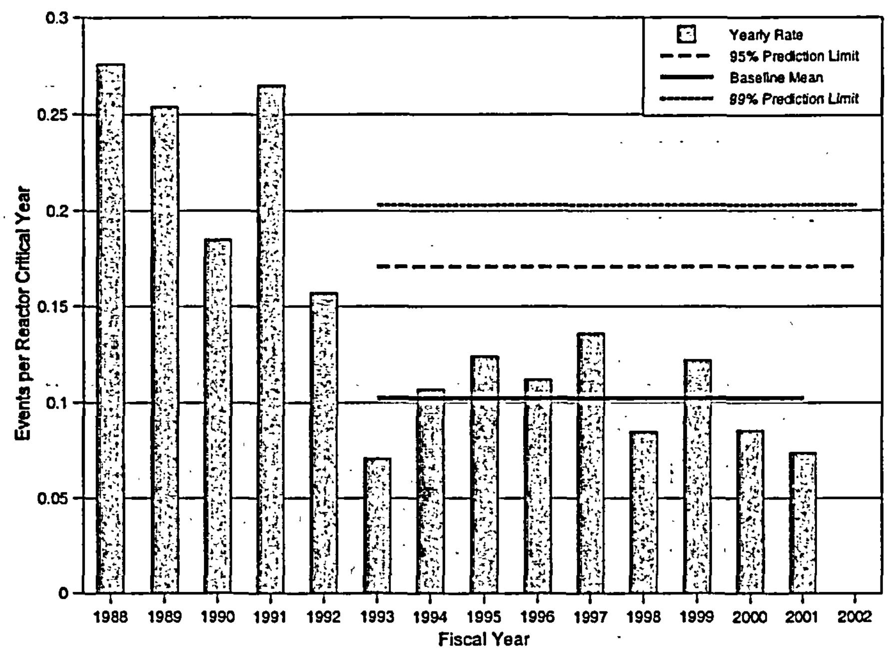

Figure 8 Loss of feedwater initiating event. The trend over the baseline period is not statistically significant (p-value = 0.726).

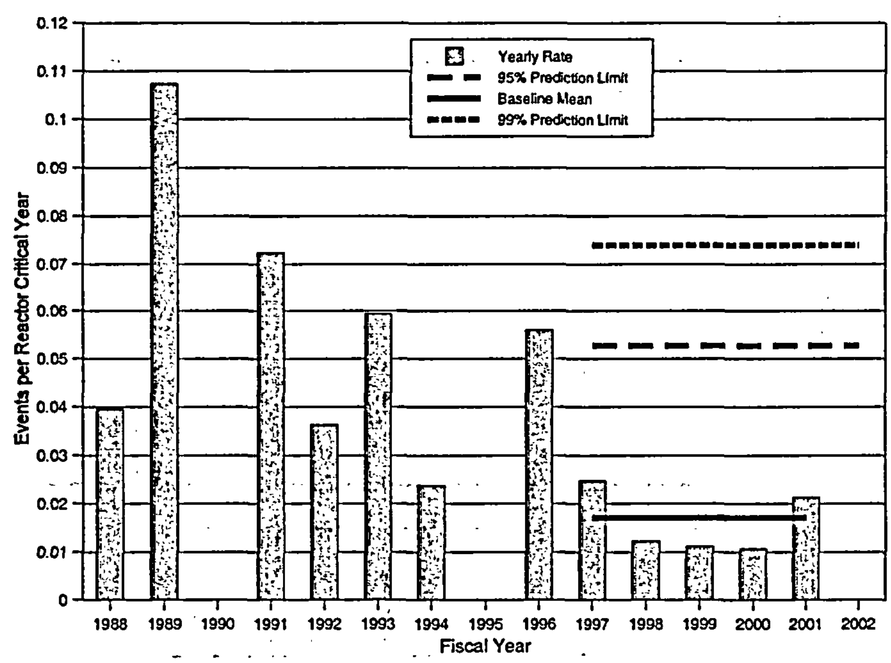

Figure 9 Loss of offsite power. The trend over the baseline period is not statistically significant (p-value = 0.613).

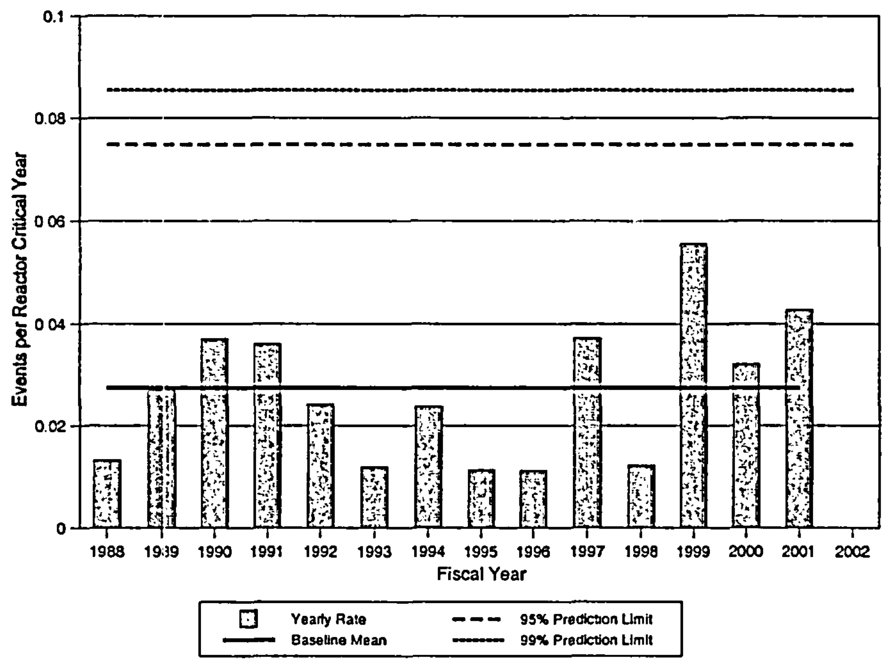

Figure 10 Loss of vital AC bus. The trend over the baseline period is not statistically significant (p-value = 0.333).

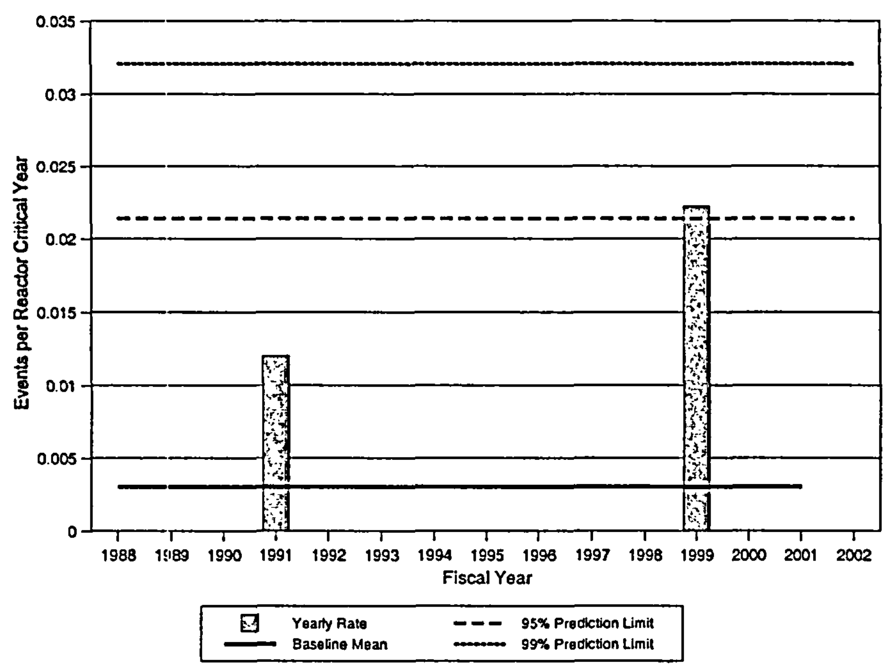

Figure 11 Loss of vital DC bus. The trend over the baseline period is not statistically significant (p-value = 0.482).

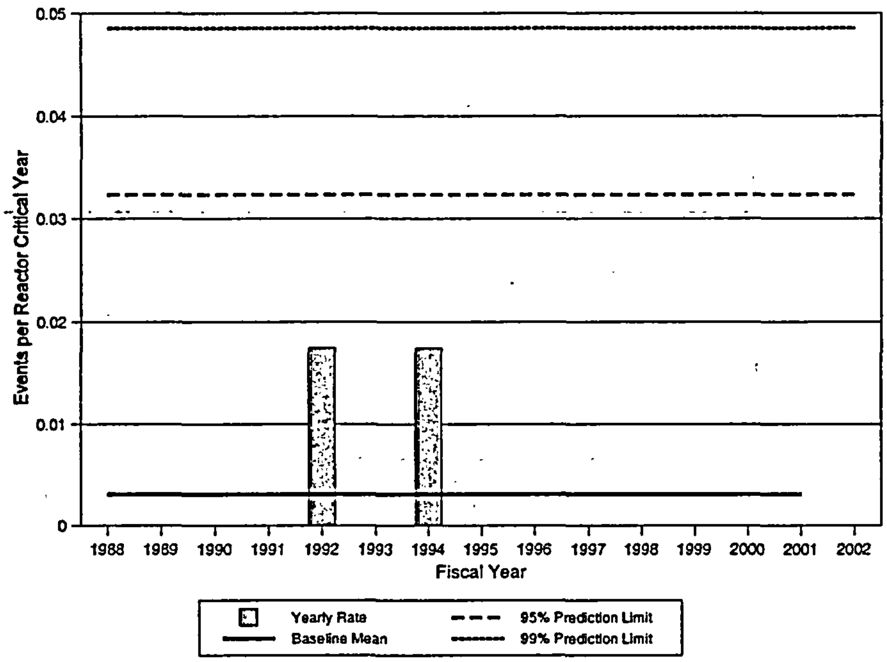

Figure 12 PWR stuck open safety/relief valve. The trend over the baseline period is not statistically significant (p-value = 0.556).

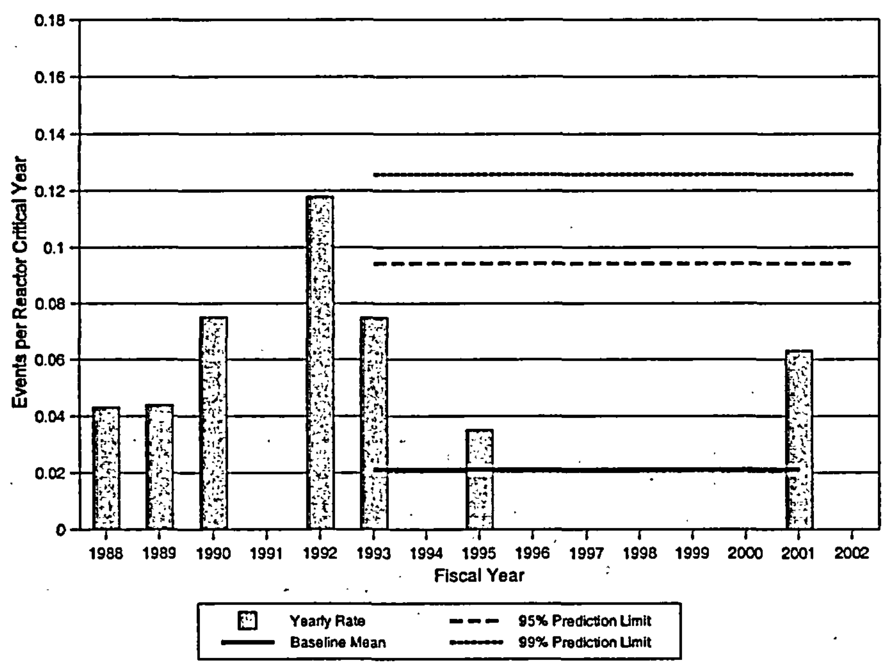

Figure 13 BWR stuck open safety/relief valve. The trend over the baseline period is not statistically significant (p-value = 0.645).

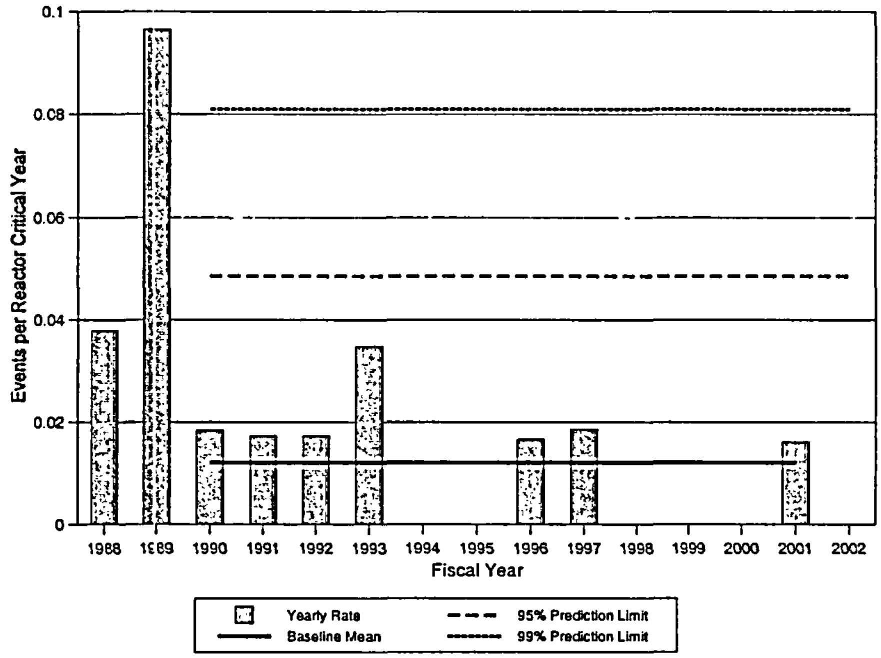

Figure 14 PWR loss of instrument air. The trend over the baseline period is not statistically significant (p-value = 0.229).

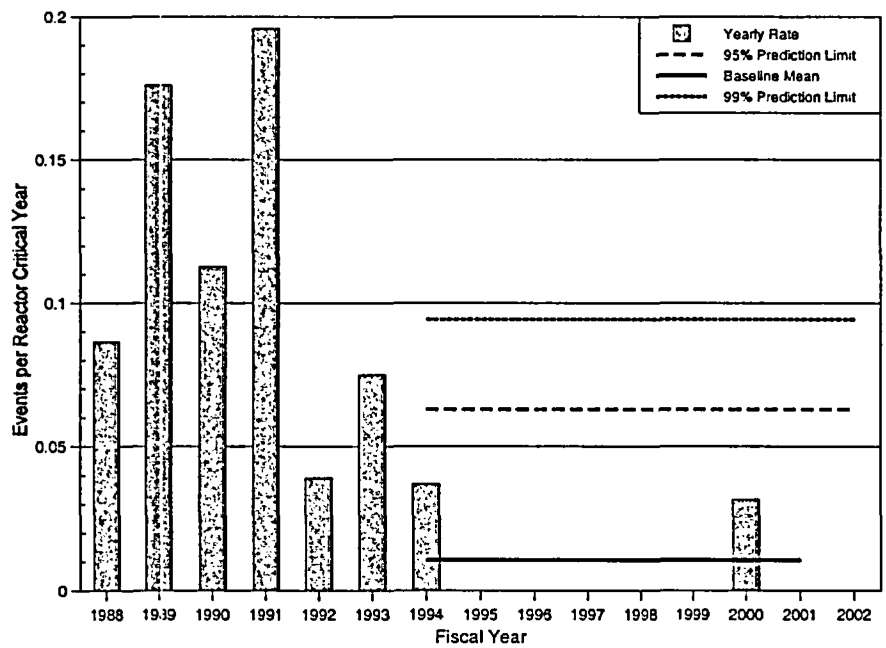

Figure 15 BWR loss of instrument air. The trend over the baseline period is not statistically significant (p-value = 0.705).

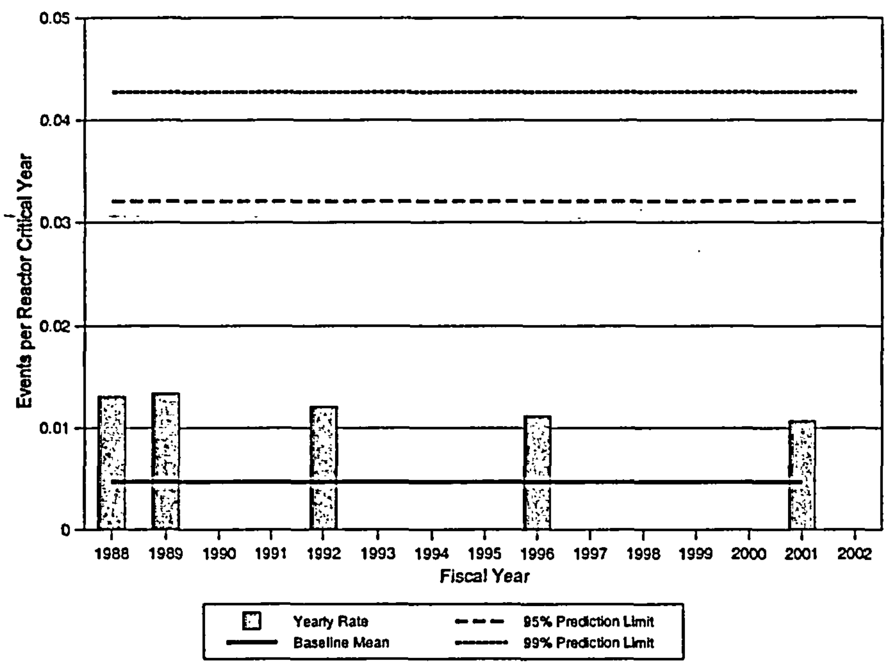

Figure 16 Small/very small loss of coolant accident. The trend over the baseline period is not statistically significant (p-value = 0.396).

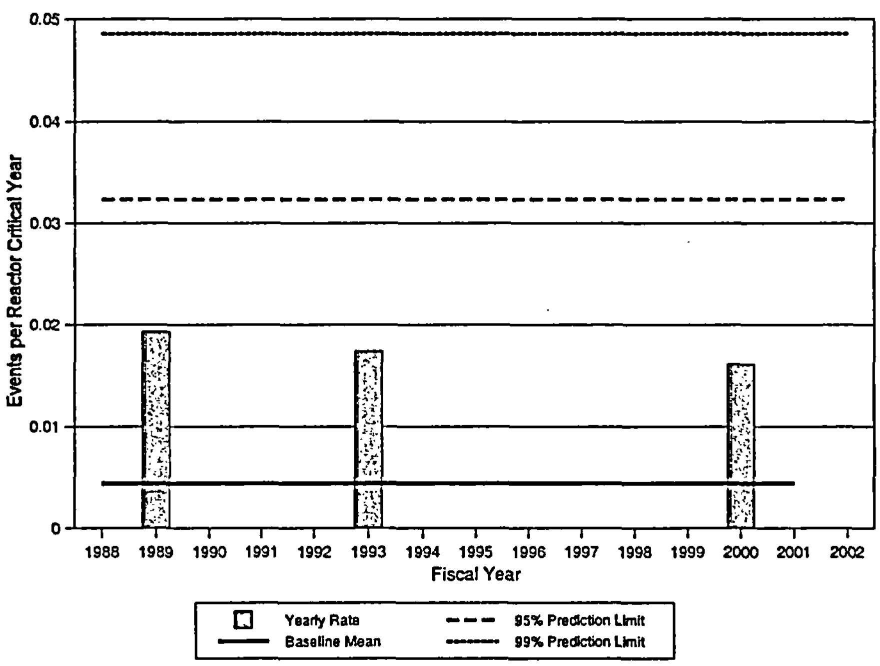

Figure 17 PWR steam generator tube rupture. The trend over the baseline period is not statistically significant (p-value = 0.776).

4. REPORTING INDUSTRY PERFORMANCE USING AN INTEGRATED INITIATING EVENT INDEX (TIER 2)

4.1 Introduction

ITP Tier 2 coverage of the Initiating Events Cornerstone of Safety involves monitoring the risk significance of changes in industry initiating event performance. Risk significance is evaluated in terms of ΔCDF. An integrated initiating events performance index is proposed. This index is termed the Baseline Risk Index for Initiating Events, or BRIIE. It combines operating experience for risk-significant initiating events with associated internal event CDF-based importance information. The measure combines frequent and infrequent events with different risk measures (Birnbaum importances). BWRs and PWRs have different core damage frequencies, which depend to some extent on different initiating events. The risk weights for various initiating events are also different for the two types of reactors. Therefore, integrated indicator results are presented for each reactor type. Although results for each reactor type could be combined into a single index, results presented in Sections 4.7 and 4.8 indicate that PWR BRIIE results would typically mask BWR BRIIE results. Because of this, a separate index for each reactor type is suggested. Figure 18 presents the concept graphically.

4.2 Risk-significant Initiating Events Covered

The risk-significant initiating events covered under the Tier 2 ITP work are the same ones used for the Tier 1 efforts. (See Section 3.2 and Table 1.)

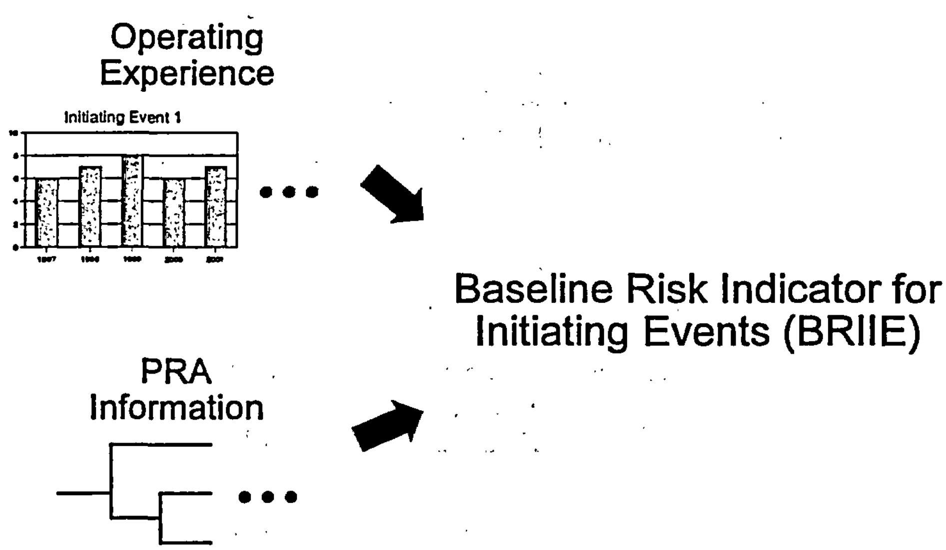

Figure 18 BRIIE overview

4.3 Mathematical Formulation of the BRIIE

The BRIIE can be evaluated on either a CDF or ΔCDF basis. Core damage frequency for a specific plant can be expressed by the following equation:

$$CDF = \sum_{i=1}^{m} B_i \lambda_{ic} \tag{3a}$$

where B_i is the partial derivative of CDF with respect to initiating event frequency λ_i. The change in core damage frequency resulting from changes in initiating event performance for a specific plant can be expressed by the following equation:

$$\Delta CDF = \sum_{i=1}^{m} B_i (\lambda_{ic} - \lambda_{ib}) \tag{3b}$$

The expression in parentheses in Equation (3b) is the current frequency of initiating event i minus the baseline frequency. Results in this report are presented using the ΔCDF approach. However, a final decision on whether to use ΔCDF or CDF has not been made. Note that Equations (3a) or (3b) are 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 the BRIIE are shown in Table 3. The choices involve the use of plant-specific information or industry-level information.

Table 3 Possible ways of estimating the BRIIE

Frequencies	Importance Measures	
	Plant Specific	Industry Average
Plant Specific	Equation 4	Equation 5
Common Industry	Equation 6	Equation 7

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

- Plant-specific current frequencies and plant-specific importance measures

$$BRIIE = \frac{1}{N} \sum_{i=1}^{m} \left(\sum_{u=1}^{N} B_{ui} (\lambda_{uic} - \lambda_{ib}) \right) \tag{4}$$

- Plant-specific current frequencies and industry-average importance measures

$$\begin{aligned} BRIIE &= \frac{1}{N} \sum_{i=1}^{m} \overline{B}_i \sum_{u=1}^{N} (\lambda_{uic} - \lambda_{ib}) \\ &= \sum_{i=1}^{m} \overline{B}_i \frac{1}{N} \sum_{u=1}^{N} (\lambda_{uic} - \lambda_{ib}) = \sum_{i=1}^{m} \overline{B}_i (\overline{\lambda}_{ic} - \lambda_{ib}) \end{aligned} \tag{5}$$

- Common industry current frequencies and plant-specific importance measures

$$
\begin{aligned}
BRIIE &= \frac{1}{N}\sum_{i=1}^{m}\sum_{u=1}^{N} B_{ui}(\lambda_{ic}^{*} - \lambda_{ib}) \\
&= \sum_{i=1}^{m}(\frac{1}{N}\sum_{u=1}^{N} B_{ui})(\lambda_{ic}^{*} - \lambda_{ib}) = \sum_{i=1}^{m} \overline{B}_i(\lambda_{ic}^{*} - \lambda_{ib})
\end{aligned}
\tag{6}
$$

- Common industry current frequencies and industry-average importance measures

$$BRIIE = \sum_{i=1}^{m} \overline{B}_i(\lambda_{ic}^{*} - \lambda_{ib}) \tag{7}$$

where

λ_{uic} = Plant-specific current frequency for initating event i at unit u

λ_{ic}^{*} = Common industry current frequency for initiating event i

λ_{ib} = Baseline frequency for initiating event i

N = Number of units (plants)

m = Number of initiating events

$\overline{\lambda}_{ic} = \frac{1}{N}\sum_{u=1}^{N} \lambda_{uic}$ = Arithmetic mean of plant-specific current frequencies

B_{ui} = Plant-specific importance measure for i^{th} IE at unit u

$\overline{B}_i = \frac{1}{N}\sum_{u=1}^{N} B_{ui} = i^{th}$ IE industry average Birnbaum importance measure

(As discussed previously, if the baseline frequencies are removed from Equations (4) through (7), then CDF rather than ΔCDF is calculated.) Note that Equations (6) and (7) are the same. Equation (4) uses plant-specific importance measures and initiating event current frequencies, and Equation (5) uses the arithmetic mean of the plant-specific initiating event current frequencies. Each common industry current frequency in Equations (6) and (7) is based on a model with a single frequency for the entire industry; this differs from assuming distinct plant-specific current frequencies and then averaging them.

Quantification of the BRIIE using all four equations and historical data is discussed in Section 4.7. The three quantities that are necessary are (1) the baseline initiating event frequencies, (2) the current initiating event frequencies, and (3) the importance measures. Each of these will now be discussed.

4.4 Baseline Performance

For each initiating event considered, a baseline period must be established over which the initiating event performance is basically constant. The baseline period is used to determine a baseline value for the initiating event. For the BRIIE, the baseline periods and baseline frequencies are those discussed in Section 3.4 and presented in Table 2.

4.5 Current Value

The current estimated frequency λ_{ic} is calculated using the information in the current period, i.e., the number of occurrences of the initiating event and the reactor critical years. This calculation can be plant-specific, using only data for the plant in question, or common industry, using data for the entire industry.

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 (e.g., one year, two years, or three years).

The following approach is recommended, based on parametric studies discussed in Appendix A, and also on the influence of events if more than one year is used. The current period is defined as the most recent year. There are two main reasons for this choice:

- The use of more than one year of data introduces dependencies between yearly results (impacts of an event remain until the event is no longer in the data period covered)
- Industry level indicators do not require as long a data collection period as plant-specific indicators.

However, use of one year, rather than two or three years, also introduces greater variability into the indicator.

The current estimates for initiating event frequencies, λ_{ic}'s, for this demonstration are obtained as follows:

- Construct the constrained noninformative prior distribution for the initiating event in question using the baseline mean frequency (Table 2). This prior is a gamma$(0.5, 1/(2\lambda_{ib}))$ distribution, where λ_{ib} is the estimated baseline frequency of the ith initiating event.
- For the current period, update this prior with current data to obtain the posterior distribution, which is gamma $(x + 0.5, t + 1/(2\lambda_{ib}))$.
- The mean of this distribution is the estimate for the current period, namely

$$\lambda_{ic} = (x + 0.5)/(t + 1/(2\lambda_{ib})).$$

4.6 Risk Information

The Birnbaum importance measure is defined as the partial derivative of CDF with respect to the initiating event frequency λ_i. 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 ΔCDF per plant.

For this study, 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 B. The SPAR models used to determine these Birnbaum importances were a combination of SPAR Rev. 3i and Rev. 3 models, available in the summer of 2002. If the BRIIE were to be formally implemented within the ITP, then the most up-to-date SPAR models should be used to re-evaluate the Birnbaums.

Table 4 Initiating event Birnbaum importance measures

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

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

4.7 BRIIE Historical Performance

Four different equations were presented in Section 4.3 for use in quantifying the BRIIE. However, two are identical, so there are really three different approaches, Equations (4), (5), and (6 or 7). All three approaches were used to calculate the BRIIE for FY 1997 through FY 2002. Mean results for each FY are presented in Figures 19 (PWRs) and 20 (BWRs).

Referring to the PWR BRIIE results in Figure 19, the quantification approach using the common industry current frequencies and industry-average Birnbaums, Equation (6 or 7), always resulted in the largest ΔCDF. This result may be surprising to some. To help explain this result, initiating event data are summarized at the industry level in Tables 5 and 6 for PWRs and BWRs. Also, the individual initiating event contributions to the PWR and BWR BRIIEs using Equation (6 or 7) are listed in Tables 7 and 8. As an example, consider the PWR BRIIE for FY 1999, with a ΔCDF of 1.08E-5/year. This value is dominated by loss of vital dc bus, with a contribution of 2.00E-5/year. Other initiating events contribute smaller positive contributions or result in negative contributions. The loss of vital dc bus contribution is large because of the two events that occurred in FY 1999, compared with an expected number significantly lower than one. The FY 1999 "current" industry frequency is (2 + 0.5)/(89.86 +

0.5/0.00296) = 9.66E-3/year (Section 4.5). The baseline frequency is 2.96E-3/year (Table 2, Section 3). Therefore, the FY 1999 industry performance was worse than the baseline by the difference 9.66E-3/year - 2.96E-3/year = 6.70E-3/year. Multiplying this change in frequency by the PWR average Birnbaum for loss of vital dc bus (Table 4) results in (2.99E-3)(6.70E-3/year) = 2.00E-5/year.

In contrast, using the plant-specific current frequencies and Birnbaums and Equation (4), the two plants with losses of vital dc bus in FY 1999 contribute 1.81E-7/year (when divided by the number of PWRs, 69), while the others all have smaller negative contributions. The plant-specific calculations result in a lower estimate of ΔCDF partially because the two losses of vital dc bus events occurred at plants with Birnbaums lower than the industry-average Birnbaum. However, if the two losses of vital dc bus had occurred at the two plants with the highest Birnbaums, their contributions to ΔCDF would have been much larger (with other plants again having small negative contributions). Therefore, although the plant-specific BRIIE calculations using Equation (4) have the potential to result in higher ΔCDF predictions (depending upon the variations in plant-specific Birnbaums and where the initiating events occur), in general the plant-specific approach will result in lower ΔCDF predictions.

Finally, Equation (5) results in a ΔCDF from losses of vital dc bus events in FY 1999 that is similar to using Equation (4), and much smaller than the result using Equation (6 or 7). In this case, however, industry-average Birnbaums are used for each plant, similar to Equation (6 or 7). The ΔCDF is much lower because of the differences in the current frequency term. In Equation (5), the industry-average current frequency is the average of plant-specific current frequencies, which are each obtained using a Bayesian update of a noninformative prior (Section 4.5) with data from only the plant in question. In Equation (6 or 7), the common industry current frequency is obtained using the same type of Bayesian update, but with industry total data. In general the industry-average current frequency will be closer to the baseline frequency than will be the common industry current frequency.

The BWR BRIIE results in Figure 20 show the same general behavior seen for the PWR BRIIE: in general Equation (6 or 7) results in larger ΔCDF predictions than do the plant-specific approaches, Equations (4) and (5). The single exception is FY 1999, where Equation (4) predicts a higher ΔCDF.

The BRIIE predictions using the common industry frequencies and industry-average Birnbaums, Equation (6 or 7), generally are the most sensitive indicator (generally predict the largest ΔCDF). Therefore, that approach to quantifying the BRIIE is suggested for use in the ITP.

Table 5 PWR initiating event data (FY 1988 through FY 2002)

Fiscal Year	Total Critical Years	PWR Critical Years	PWR General Transients	PWR Loss of Heat Sink	Loss of Feed-water	Loss of Offsite Power	Loss of Vital AC Bus	Loss of Vital DC Bus	PWR Stuck Open SRV	PWR Loss of Instrument Air	Small/Very Small Break LOCA	PWR Steam Generator Tube Rupture
1988	75.88	52.72	175	6	21	3	1	0	0	2	1	0
1989	74.52	51.79	149	12	19	8	2	0	0	5	1	1
1990	80.81	54.20	127	10	15	0	3	0	0	1	0	0
1991	82.94	57.42	110	6	22	6	3	1	0	1	0	0
1992	82.68	57.24	126	7	13	3	2	0	1	1	1	0
1993	84.19	57.52	94	5	6	5	1	0	0	2	0	1
1994	84.12	57.26	80	9	9	2	2	0	1	0	0	0
1995	88.53	60.09	82	4	11	0	1	0	0	0	0	0
1996	89.23	59.91	75	7	10	5	1	0	0	1	1	0
1997	80.68	53.50	54	3	11	2	3	0	0	1	0	0
1998	81.89	55.00	40	3	7	1	1	0	0	0	0	0
1999	89.86	60.30	55	3	11	1	5	2	0	0	0	0
2000	93.44	61.95	42	7	8	1	3	0	0	0	0	1
2001	93.49	61.72	45	8	7	2	4	0	0	1	1	0
2002	94.73	62.76	30	3	2	1	3	0	0	1	0	0

Table 6 BWR initiating event data (FY 1988 through FY 2002)

Fiscal Year	Total Critical Years	BWR Critical Years	BWR General Transients	BWR Loss of Heat Sink	Loss of Feed-water	Loss of Offsite Power	Loss of Vital AC Bus	Loss of Vital DC Bus	BWR Stuck Open SRV	BWR Loss of Instrument Air	Small/Very Small Break LOCA
1988	75.88	23.16	71	15	21	3	1	0	1	2	1
1989	74.52	22.73	57	17	19	8	2	0	1	4	1
1990	80.81	26.61	57	12	15	0	3	0	2	3	0
1991	82.94	25.52	57	11	22	6	3	1	0	5	0
1992	82.68	25.44	49	9	13	3	2	0	3	1	1
1993	84.19	26.67	50	15	6	5	1	0	2	2	0
1994	84.12	26.86	45	8	9	2	2	0	0	1	0
1995	88.53	28.44	51	10	11	0	1	0	1	0	0
1996	89.23	29.32	38	5	10	5	1	0	0	0	1
1997	80.68	27.18	24	4	11	2	3	0	0	0	0
1998	81.89	26.89	26	7	7	1	1	0	0	0	0
1999	89.86	29.56	28	7	11	1	5	2	0	0	0
2000	93.44	31.49	29	8	8	1	3	0	0	1	0
2001	93.49	31.77	24	2	7	2	4	0	2	0	1
2002	94.73	31.97	22	6	2	1	3	0	1	0	0

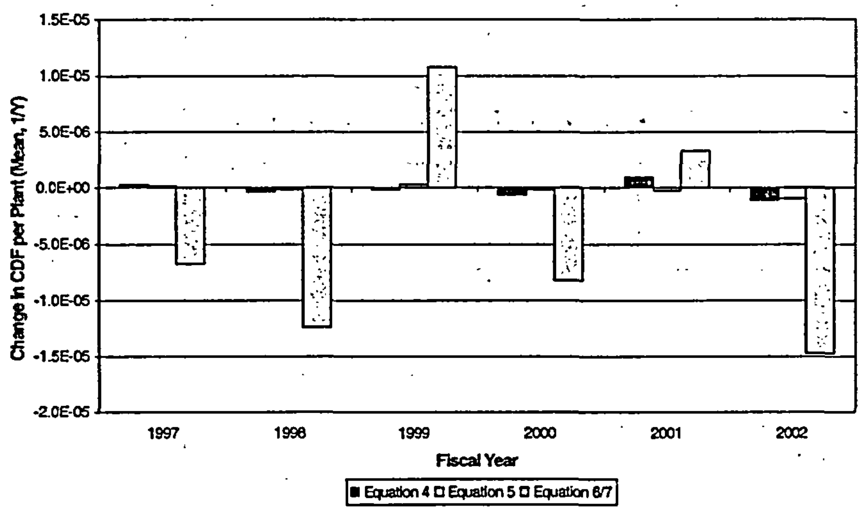

Figure 19 PWR BRIIE historical performance using equations (4), (5), and (6/7)

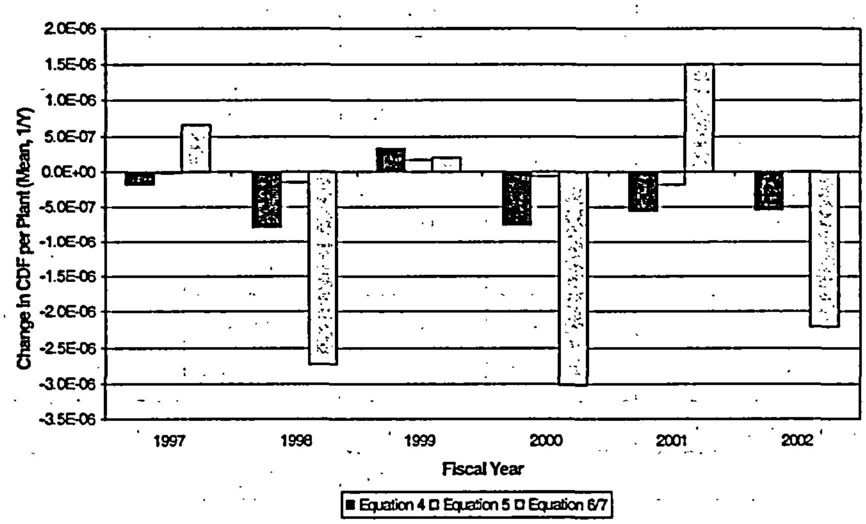

Figure 20 BWR BRIIE historical performance using equations (4), (5), and (6/7)

Table 7 PWR BRIIE contributions using equation 6 or 7 (FY 1997 through FY 2002)

Initiating Event	FY1997	FY1998	FY1999	FY2000	FY2001	FY 2002
General Transients	4.72E-7	-7.35E-8	2.96E-7	-1.71E-7	-7.07E-8	-5.71E-7
Loss of Heat Sink	-7.01E-7	-7.40E-7	-8.29E-7	2.72E-7	5.59E-7	-8.66E-7
Loss of Feedwater	6.36E-7	-3.04E-7	3.56E-7	-3.03E-7	-4.97E-7	-1.46E-6
Loss of Offsite Power	1.92E-6	-1.17E-6	-1.46E-6	-1.58E-6	1.06E-6	-1.62E-6
Loss of Vital AC Bus	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Loss of Vital DC Bus	-2.83E-6	-2.89E-6	2.00E-5	-3.15E-6	-3.15E-6	-3.18E-6
Stuck Open SRV	-4.94E-7	-5.08E-7	-5.43E-7	-5.54E-7	-5.53E-7	-5.60E-7
Loss of Instrument Air	3.14E-7	-5.85E-7	-6.07E-7	-6.14E-7	1.99E-7	1.88E-7
Small/Very Small Break LOCA	-4.93E-6	-5.02E-6	-5.28E-6	-5.39E-6	7.00E-6	-5.43E-7
Steam Generator Tube Rupture	-1.09E-6	-1.12E-6	-1.19E-6	3.26E-6	-1.21E-6	-1.22E-6
BRIIE Total (ΔCDF)	-6.71E-6	-1.24E-5	1.08E-5	-8.23E-6	3.34E-6	-1.47E-5

Table 8 BWR BRIIE contributions using equation 6 or 7 (FY 1997 through FY 2002)

Initiating Event	FY1997	FY1998	FY1999	FY2000	FY2001	FY 2002
General Transients	-4.07E-8	9.53E-8	6.92E-8	3.45E-8	-1.88E-7	-2.78E-7
Loss of Heat Sink	-3.05E-7	5.39E-7	3.61E-7	4.98E-7	-9.92E-7	-1.96E-8
Loss of Feedwater	4.89E-7	-2.34E-7	2.74E-7	-2.33E-7	-3.82E-7	-1.12E-6
Loss of Offsite Power	1.90E-6	-1.15E-6	-1.44E-6	-1.56E-6	1.05E-6	-1.60E-6
Loss of Vital AC Bus	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Loss of Vital DC Bus	-2.56E-7	-2.61E-7	1.81E-6	-2.85E-7	-2.85E-7	-2.88E-7
Stuck Open SRV	-5.33E-7	-5.36E-7	-5.60E-7	-5.75E-7	1.13E-6	2.71E-7
Loss of Instrument Air	-3.23E-8	-3.25E-8	-3.45E-8	6.96E-8	-3.61E-8	-3.62E-8
Small/Very Small Break LOCA	-1.11E-7	-1.13E-7	-1.19E-7	-1.22E-7	1.58E-7	-1.23E-7
BRIIE Total (ΔCDF)	1.11E-6	-1.70E-6	3.60E-7	-2.17E-6	4.56E-7	-3.20E-6

4.8 BRIIE Simulation and Uncertainty

The historical performance of the BRIIE over the period FY 1997 through FY 2002 provides a limited picture of expected performance of the BRIIE. To provide additional insight, the predictive distribution for the BRIIE was evaluated by simulation. That is, for each kind of initiating event, simulate many values of λ_i^* from its predictive distribution. (The predictive distribution is explained in Section 3.5.) Calculate the resulting values of the BRIIE, and observe the resulting mean, variance, and percentiles.

Simulation results for the PWR BRIIE are presented in Figures 21 and 22. These results were obtained using one year of data and a Bayesian update of a noninformative prior, assuming the data occur under baseline conditions. The simulation result presented in Figure 21 includes both aleatory uncertainty (the randomness of the event count in the future year) and epistemic uncertainty (lack of perfect knowledge of the value of the baseline frequency). However, it does not include uncertainty in the industry-average Birnbaums. Simulation results with and without Birnbaum uncertainty are compared in Figure 22. On a ΔCDF basis, the 95% for the PWR BRIIE is 2.12E-5/year without Birnbaum uncertainty included and 2.32E-5/year with Birnbaum uncertainty. Corresponding 99% values are 3.27E-5/year and 4.47E-5/year.

Simulation results for the BWR BRIIE are presented in Figures 23 and 24. On a ΔCDF basis, the 95% for the BWR BRIIE is 6.30E-6/year without Birnbaum uncertainty included and 6.70E-6/year with Birnbaum uncertainty. Corresponding 99% values are 9.78E-5/year and 1.22E-5/year.

As discussed in Appendix A, Section A.2.2.3, the BRIIE simulation results without Birnbaum uncertainty are recommended to be used in setting the BRIIE reporting thresholds. This recommendation is based on the interpretation of the BRIIE as an index to be calculated given fixed weighting factors (the Birnbaums). Treatment of Birnbaum uncertainty is not thought to be relevant for the predictive distribution of the BRIIE. By definition, the predictive distribution is conditional on data observed in the past, and the past data and SPAR models determine the estimated Birnbaum importances. These values for the Birnbaum importances are then built into the formula for the BRIIE.

4.9 BRIIE Sensitivity

A sensitivity study was performed to evaluate the impacts on the BRIIE from individual initiating events. For each initiator, the 95% and 99% prediction limits (from Section 3, Table 2) were inserted into the BRIIE, while keeping other initiating events at their baseline frequencies. The results of these sensitivity evaluations are presented in Figures 25 and 26 for PWRs and BWRs, respectively. For PWRs, the largest contributors to the BRIIE are the small/very small break LOCA and loss of vital DC bus. For the BWRs, the largest contributor is loss of offsite power.

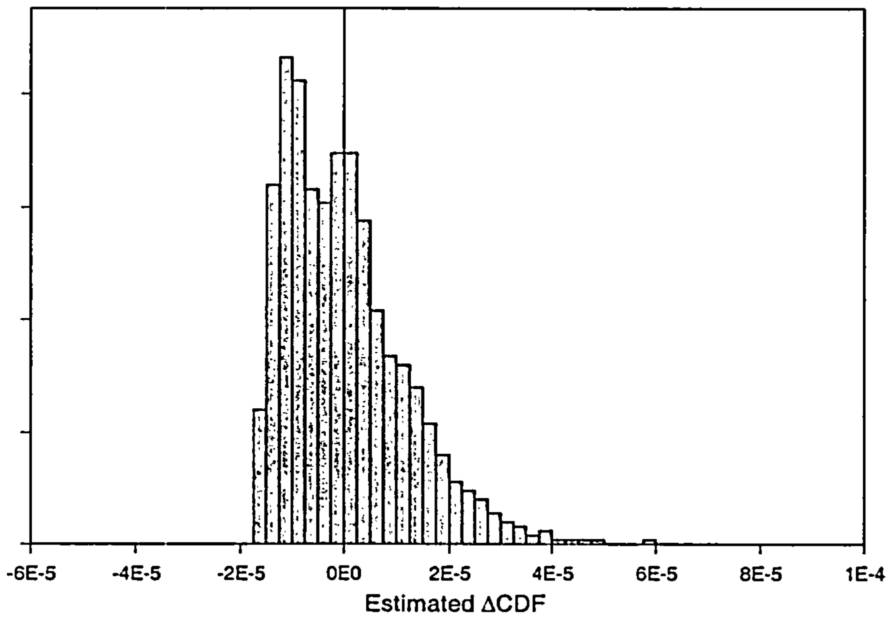

Figure 21 PWR BRIIE simulation results (ΔCDF) without Birnbaum uncertainty

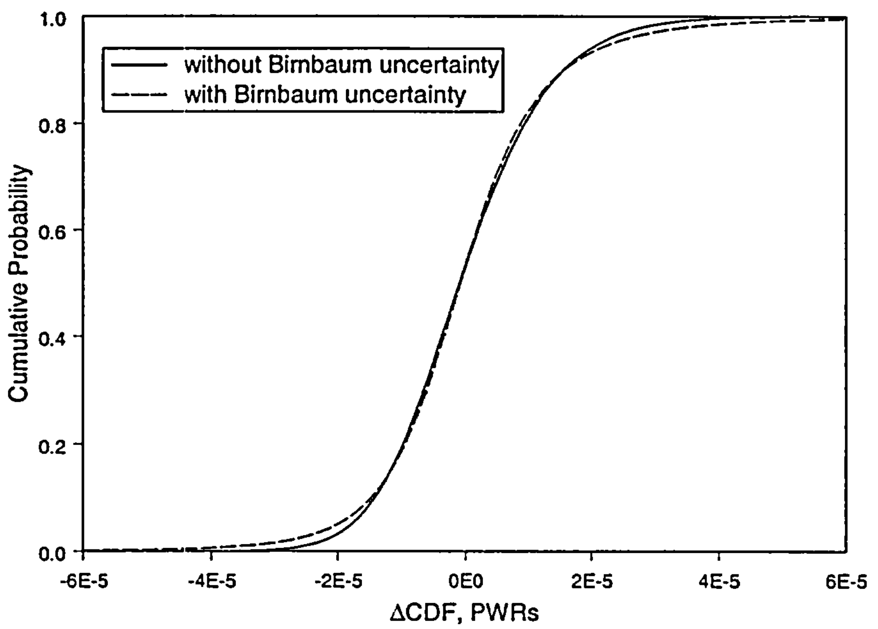

Figure 22 PWR BRIIE simulation results (ΔCDF) with and without Birnbaum uncertainty

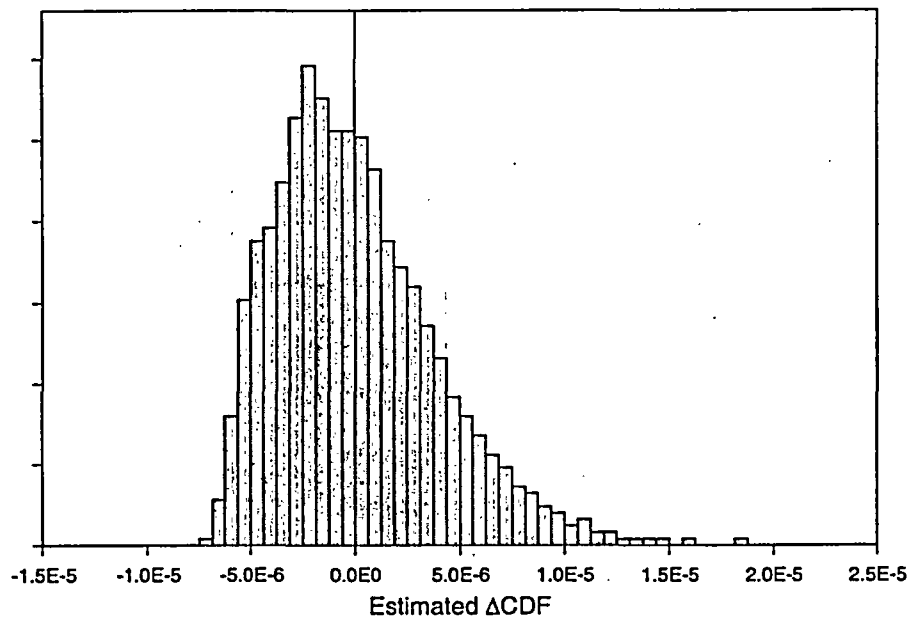

Figure 23 BWR BRIIE simulation results (ΔCDF) without Birnbaum uncertainty

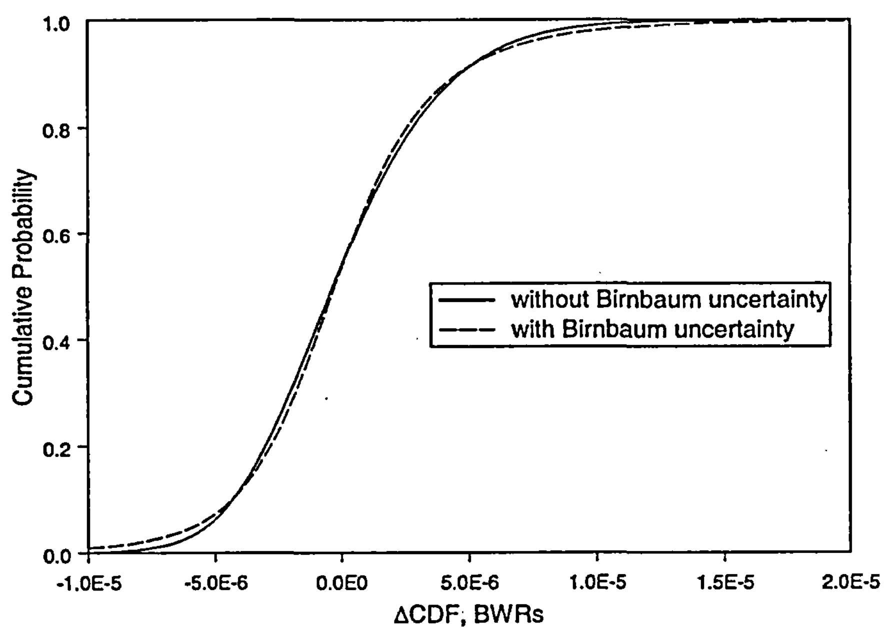

Figure 24 BWR BRIIE simulation results (ΔCDF) with and without Birnbaum uncertainty

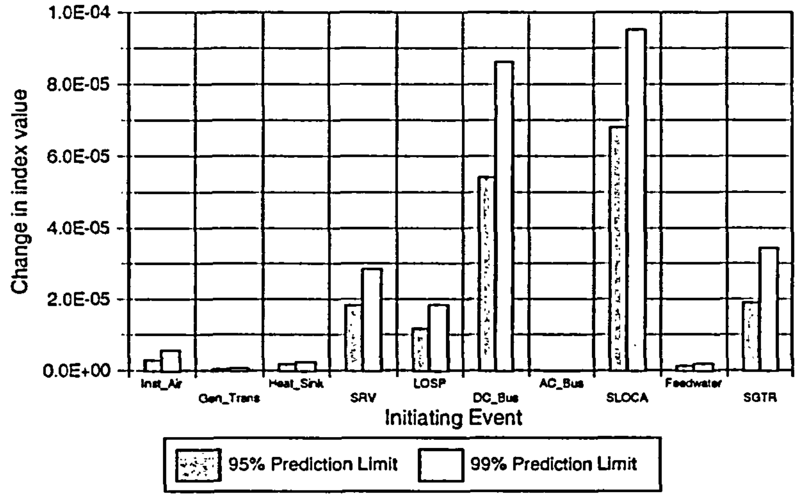

Figure 25 PWR BRIIE (ΔCDF) sensitivity to individual initiating event 95% and 99% prediction limits

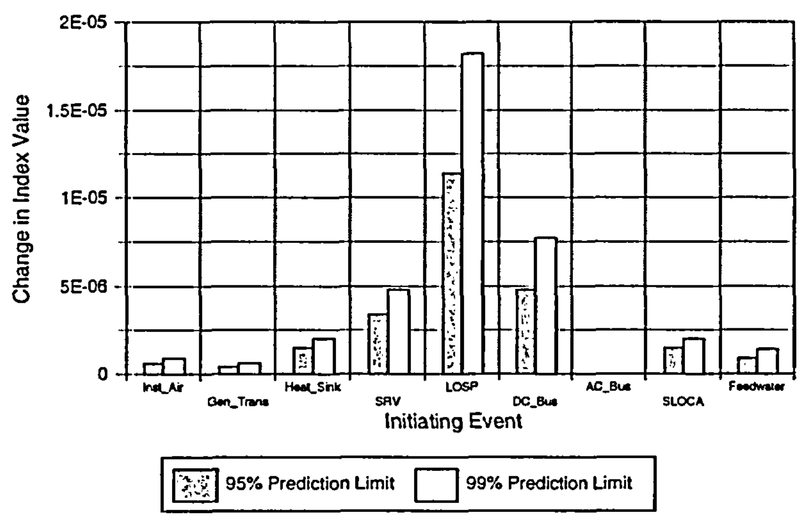

Figure 26 BWR BRIIE (ΔCDF) sensitivity to individual initiating event 95% and 99% prediction limits

4.10 Thresholds for the BRIIE

Risk-informed thresholds need to be established for the two BRIIEs for reporting to Congress. 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 reporting thresholds for the two BRIIEs be established considering the following information:

- Uncertainty in the BRIIEs 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 BRIIEs
- Sensitivity of BRIIEs 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.

5. ILLUSTRATIVE INITIATING EVENT TREND EXAMPLES

In this section we present four examples to show how the ITP could treat initiating event trends. Recall that the ITP is monitoring trends from two perspectives: (1) an increase in the number of events in a given year (measured by exceeding a prediction limit), and (2) the start of an emerging trend.

5.1 Small/Very Small Break LOCA Example

Suppose we observe four events in one year that are classified as small/very small break LOCAs. Each event occurred in a separate plant. This initiating event is very rare. The 95% prediction limit is three events, and the 99% prediction limit is 4 events. We have exceeded the 95% prediction limit and hit the 99% prediction limit. Because the number of actual events exceeds the prediction limit, this initiating event is a candidate for further investigation.

Because small LOCAs do not occur very often, NRC would probably look at each event in more detail after it had occurred. Thus, NRC would have inspectors and staff reviewing the each event. The ITP would look at these events to see if there were similarities among the events and to provide any lessons learned from this evaluation. These lessons would be communicated to the industry via some type of generic communication. Further regulatory action would probably not be necessary since the NRC investigated each event in detail.

5.2 Increase in General Transients

In this example, we see a marked increase in the number of PWR general transients. We observe 74 general transients for the year. This exceeds both the 95% and 99% prediction limits, which are 61 and 67 respectively. However, no unit has exceeded the white/green ROP threshold for scrams. The ITP investigates this situation and finds that the majority of the scrams occurred at Westinghouse plants. Further investigation reveals that a given device has been the cause of the majority of the general transients.

5.3 Loss of Heat Sink Trend

In this example we consider the PWR loss of heat sink initiator shown in Figure 7. The figure shows that a trend is starting from FY 1999 through FY 2001. We have observed three, seven, and eight events in each of the three years, respectively. The expected number of events in a year is about six. None of the prediction limits have been exceeded, which are 12 and 14. However, the fact that we have had an increase in three consecutive years alerts the ITP that this initiating event should be monitored. Action is not pursued for two reasons. First, the number of observed events has not exceeded the prediction limits. In fact, the observed number is close to the mean. Secondly, we want to see what happens in FY 2002. In that year three events occurred. So the trend is not sustained.

We note that two or even three consecutive increases do not constitute strong evidence of a trend. Any three distinct numbers can be arranged in six ways, and in only one arrangement are the three numbers increasing. So if the counts are simply bouncing around at random, the chance of seeing such an increase is $1/6 = 0.17$. This argument justifies the stated decision to wait for another year.

5.4 Loss of Offsite Power Grid Event

As a final example, the power distribution grid disturbance event that occurred in the Northeastern and Midwestern portions of the U.S. on August 14, 2003 is considered. That single event resulted in losses of offsite power to nine U.S. commercial nuclear power plants that were at power before the event occurred. These nine events by themselves, not counting other losses of offsite power that might have occurred during FY 2003, are used in the following to illustrate the use of the predictive distribution and prediction limits. (The actual review of LERs for FY 2003 is not yet complete).

The 95% and 99% prediction limits for losses of offsite power events for a year are given in Table 2. They are 5 and 7 events respectively. The number losses of offsite power, nine, exceeds both prediction limits. In fact, the probability of having nine or more losses of offsite power in a given year is 4.3E-4. It is a number calculated from a formula that assumes the losses are independent of each other, occurring at some underlying constant rate. We choose to model the baseline in this way, not because we necessarily think it is true, but rather because it is our purpose to detect significant deviations from these special conditions. This small probability indicates that there has been a departure from past operating experience during the baseline period (FY 1997 – FY 2001). This is a flag for further investigation, which has already been initiated by the NRC.

Past studies of losses of offsite power, including NUREG-1032 (Baranowsky 1988) and NUREG/CR-5496 (Atwood et al. 1998) have indicated that grid-related losses of offsite power are rare. The last such event was in 1989. Therefore, NRC might attempt to determine whether the August 14, 2003 event is a rare, random event or whether this event might be the start of more frequent grid-related losses of offsite power. If the latter appears to be the case, then additional work may be warranted to identify appropriate longer term regulatory response.

Finally, the risk-significance of the August 14, 2003 grid disturbance event within the ITP would be evaluated within the context of the BRIIE. Initiating event data for the entire period for FY 2003 are not yet available. However, if all other risk-significant initiating events are assumed to be at their baseline frequencies, then the PWR and BWR BRIIEs assuming nine losses of offsite power would both be approximately 2.5E-5/y on a ΔCDF basis. Thresholds are needed to judge the significance of the BRIIE for reporting to Congress.

6. RECOMMENDATIONS, INSIGHTS, AND IMPLEMENTATION CONSIDERATIONS

This report identifies several potential enhancements to the existing ITP, covering the Initiating Events Cornerstone of Safety. A two-tiered approach to monitoring and evaluating risk-significant initiating event performance at the industry level is suggested, following the existing structure of the ITP. The Tier 1 activity includes trending 10 risk-significant initiating events (nine for BWRs) and monitoring yearly industry performance against prediction limits. The Tier 2 activity integrates the individual initiating event performance into the BRIIE, a risk-based (ΔCDF) index evaluated separately for PWRs and BWRs. The yearly BRIIE results are then compared with thresholds.

<u>Recommendations for Tier 1</u>

<u>Recommendation 1</u> Use the current baseline periods identified in this report, determined by the statistical analysis and the associated rules discussed. Update the baseline periods only when strong evidence exists that something has changed.

<u>Recommendation 2</u> Use predictive distributions and resulting prediction limits to monitor the occurrences of events during the current year. Predictive limits provide a means for measuring when things are starting to deviate from the baseline conditions.

<u>Recommendation 3</u> Monitor the recent period for emerging trends in the individual initiating event types.

<u>Recommendations for Tier 2</u>

<u>Recommendation 4</u> Use industry-average Birnbaum importances and industry initiating event frequencies to calculate the BRIIE. Four equations for calculating the BRIIE are identified in the report. They are the following:

- Plant-specific Birnbaum importances and plant-specific initiating event frequencies
- Industry-average Birnbaum importances and plant-specific initiating event frequencies
- Plant-specific Birnbaum importances and industry initiating event frequencies
- Industry-average Birnbaum importances and industry initiating event frequencies

The last two cases yield the same results. Section 4.7 discusses the reasons for the choice stated in Recommendation 4. In most cases, the recommended choice results in the largest ΔCDF estimate and is therefore the most sensitive indicator.

<u>Recommendation 5</u> To determine estimates of current initiating event frequencies, use Bayesian updates instead of maximum likelihood estimators. This recommendation is in line with other ongoing NRC efforts, such as the Mitigating Systems Performance Index (MSPI) pilot program.

<u>Recommendation 6</u> To determine estimates of current initiating event frequencies, use a rolling one-year data window and not a two- or three-year data window. At the industry level, one year of data provides enough information to evaluate the initiating events covered in this report. Also, use of one year of data eliminates any data dependencies between the baseline frequencies and the current frequencies. Finally, if two or three years of data are used, the influence of events

occurring in one year can be masked by more influential events that occurred in a previous year. For example, the recent grid event of August 14, 2003, resulted in loss of offsite power to nine plants. If a two- or three-year window were used, these occurrences would dominate the BRIIE for the entire period.

Recommendation 7 An expert panel should be formed for selecting the appropriate prediction limits for the individual initiating event trends and also the thresholds for the PWR and BWR BRIIEs. Uncertainty and sensitivity information presented in Section 4, as will as policy and other considerations, would be used to make the selection of the threshold values.

Additional Insights

Insight 1 BRIIE calculations can be done on a CDF or ΔCDF basis. Either one can be used. This report used ΔCDF. The majority of reviewers suggested that ΔCDF be used.

Insight 2 No additional information is needed from industry. Data for these initiating events -- numbers of events and corresponding reactor critical years -- are already being collected and analyzed by the NRC on a continual basis.

Insight 3 The BRIIE results are sensitive to the industry-average Birnbaum values. Therefore, accurate Birnbaums are needed for the BRIIE.

Implementation Considerations

In order to implement the proposed Tier 1 and 2 activities into the ITP, the following steps need to be taken:

1. The staff can easily calculate the prediction limits for the Tier 1 individual initiating events, for any data window that may be of interest. This can be implemented very easily with little effort and cost.

2. Conduct a pilot exercise to set thresholds based on the current example calculations. From this we can learn what is the best way to present information to a panel and what additional information would be helpful when setting the thresholds.

3. The Birnbaum importance measures used to quantify the PWR and BWR BRIIEs were obtained from SPAR Rev. 3i and 3 models in the summer of 2002 for this demonstration exercise. Final Birnbaums should be obtained from the improved SPAR Rev. 3 models being completed by the NRC. The initiating event frequencies and the basic event failure probabilities should be updated before the final Birnbaum importance measures are estimated.
4. Perform studies using the SPAR models to provide information about the robustness of the BRIIE. Compare with industry PRA models where possible.

5. Develop procedures, process, and quality assurance guides for the Tier 1 and Tier 2 activities.

6. The proposed Tier 1 and 2 activities should be formally incorporated into the ITP over a several-year period. This allows for refinements or enhancements as experience with these activities is accumulated.

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APPENDIX A

BRIIE Simulation, Uncertainty, and Sensitivity Results

CONTENTS

FIGURES

TABLES

A.1 OUTLINE

This appendix deals with several topics:

- Baseline Core Damage Frequency (CDF)
  - Uncertainty in the baseline CDF, resulting from uncertainty in the initiating-event frequencies and uncertainty in the Birnbaum importances.
  - Identification of particular initiating events that contribute most to estimated CDF or its uncertainty, as a result of their high (industry mean) Birnbaum importances

- BRIIE, the estimate of change in core damage frequency (ΔCDF).
  - Uncertainty in BRIIE, resulting from uncertainty in the initiating-event frequencies and in the Birnbaum importances.
  - Predictive distribution of BRIIE, including determination of selected percentiles.

- Sensitivity of BRIIE to departures from baseline conditions.

- Investigation of the variation between plants in the Birnbaum importances.

After an introductory section, each of the above topics is considered, first for PWRs and then for BWRs.

A.2 INTRODUCTION

A.2.1 Estimates of CDF and ΔCDF

Core damage frequency can be expressed by the following equation:

$$CDF = \sum_{i=1}^{m} B_i \lambda_i \tag{A-1}$$

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 the report. 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 average for boiling water reactors (BWRs) and one average for pressurized water reactors (PWRs). In Section A.6, however, the plant-specific Birnbaum importances are examined.

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 BRIIE (CDF) would be minimal. Also, experimentation with different formulas has shown that assuming a common initiating-event frequency gives an estimator that is most sensitive to the data; the other formulas tend to strongly damp out variations in the event counts.

Finally, the index BRIIE is defined as an estimate of ΔCDF:

$$BRIIE = \sum_{i=1}^{m} B_i(\lambda_i - \lambda_{i\,base}) \quad \text{(A-2)}$$

Here λ_i is the estimate of the current value, and $\lambda_{i,\,base}$ is the estimated baseline value.

A.2.2 Uncertainty and Variability

A.2.2.1 Random Variability of Data.

The future estimate of λ_i is uncertain because of random variability in the future data counts. The distribution of the count depends on the true λ_i and the length of the future observation period (one industry-year in this report). This uncertainty/variability is considered throughout this report.

A.2.2.2 Uncertainty in Baseline Frequencies

The true λ_i is uncertain, even if baseline conditions persist, because the baseline value is estimated from baseline data. This uncertainty is considered in all portions of this report that assume baseline conditions. It is quantified by assuming a Jeffreys noninformative prior on λ_i, using the baseline data, and obtaining the Bayes posterior distribution for λ_i.

A.2.2.3 Uncertainty in the Birnbaum Importances

The Birnbaum importances are uncertain, because they are estimated from the cutset probabilities in the SPAR models. There are two perspectives on this. One is that the true CDF or ΔCDF is to be estimated. In that case, the uncertainty in the Birnbaum importances should be considered. The other perspective, at least for BRIIE, is that the Birnbaum importances are known weighting factors used in a formula for an index, motivated by ΔCDF but still just an index. For this index, only the uncertainties in the λ_i values must be considered.

It turns out that uncertainty in B_i is less important for BRIIE than for the estimate of CDF. As can be seen from Equation (A-2), if the estimated current λ_i is close to the baseline value then uncertainty in B_i has little effect. This is discussed more in Section A.4.1.

For these reasons, uncertainty in the Birnbaum importances will be considered below with the estimate of baseline CDF, but will normally not be considered with simulations of BRIIE.

It is not easy to quantify the uncertainty in the industry-average Birnbaum importance. Only a rough quantification has been attempted here. Based on experience with the SPAR models, each Birnbaum importance was assumed to have an uncertainty distribution that is lognormal with error factor EF = 5. Units with identical SPAR models were assumed to have identical Birnbaum importances, *i.e.* the uncertainties were perfectly correlated. Units with distinct SPAR models were assumed to have independent uncertainties for their Birnbaum importances, although this independence assumption may be overly optimistic. The mean and variance of the industry-average Birnbaum importance were then found using standard formulas for the mean and variance of an average. The uncertainty distribution of the average Birnbaum importance was assigned a lognormal distribution with the mean and variance that were just found. When this was done, it turned out that the average of the error factors for the 15 Birnbaum importances was about 1.7.

A.2.2.4 Between-Plant Variability

Finally, between-plant variability in this document always refers only 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.

A.3 ESTIMATED BASELINE CDF

The estimated baseline CDFs are examined here, for BWRs and PWRs. The main contributors to the estimates and their uncertainties are identified. The estimated baseline CDFs are given, and the uncertainties in the estimates are quantified.

A.3.1 PWR Baseline CDF

Table A-1 shows the contributions to the mean and variance of the baseline CDF, for PWRs That is, the various initiating-event frequencies are quantified by Bayesian distributions with gamma form, yielding a Bayesian distribution for the baseline CDF. Elsewhere when the "baseline CDF" is given as a number, it is the mean of this distribution, 3.79×10^{-5}

If the Birnbaum importances are regarded as known, 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 without Birnbaum uncertainty" column is of the form $B_i a_i/b_i^2$. If, instead, the Birnbaum importances are regarded as uncertain, the *i*th element of the "Mean" column is of the form $E(B_i)a_i/b_i$. The corresponding element of the column "Variance Including Birnbaum Uncertainty" includes both the variance of λ_i and the variance of B_i. The two interpretations of the mean give identical numbers, but the two interpretations of variance are shown in separate columns.

From the "Total" row, when all uncertainties are considered, the variance of the Bayesian distribution of the CDF is 2.11×10^{-10}. Thus, two standard deviations equal about 2.9×10^{-5}, and the true baseline 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 CDF are found to be 2.68×10^{-5} and 5.13×10^{-5} when only the uncertainty in the initiating-event frequencies is considered. When the uncertainty in the Birnbaum importances is also considered, the 5th and 95th percentiles are farther apart, 2.19×10^{-5} and 6.37×10^{-5}. The units are events per reactor-critical year in every case. The Bayesian distribution of baseline CDF is shown in Figures A-1 and A-2, when the uncertainty in the Birnbaum importances is ignored or included, respectively. The vertical line in the figures shows the mean.

Table A-1 Breakdown of PWR Baseline CDF by Initiating Event

Initiating Event	Mean of Baseline CDF		Variance, without Birnbaum Uncertainty		Variance, Including Birnbaum Uncertainty		Baseline Prior, Gamma(a, b)		Mean Birnbaum Importance
							a	b	
Small LOCA	1.17E-5	31%	2.50E-11	44%	1.47E-10	69%	5.5	1182.26	2.52E-3
Loss of DC Bus	8.85E-6	23%	2.24E-11	39%	4.83E-11	23%	3.5	1182.26	2.99E-3
Loss of Offsite Power	5.55E-6	15%	4.10E-12	7%	6.70E-12	3%	7.5	439.36	3.25E-4
PWR Steam Generator Tube Rupture	3.45E-6	9%	3.40E-12	6%	4.14E-12	2%	3.5	800.62	7.89E-4
PWR Stuck Open SRV	1.99E-6	5%	1.58E-12	3%	2.20E-12	1%	2.5	800.62	6.36E-4
Loss of Feedwater	1.94E-6	5%	4.66E-14	0%	6.23E-13	0%	80.5	785.43	1.89E-5
PWR Loss of Heat Sink	1.84E-6	5%	5.42E-14	0%	4.07E-13	0%	62.5	641.91	1.89E-5
PWR General Transient	1.54E-6	4%	1.30E-14	0%	3.44E-13	0%	182.5	238.97	2.02E-6
PWR Loss of Instrument Air	1.02E-6	3%	1.22E-13	0%	1.73E-12	1%	8.5	696.11	8.35E-5
CDF Total	3.79E-5	100%	5.56E-11	100%	2.11E-10	100%			

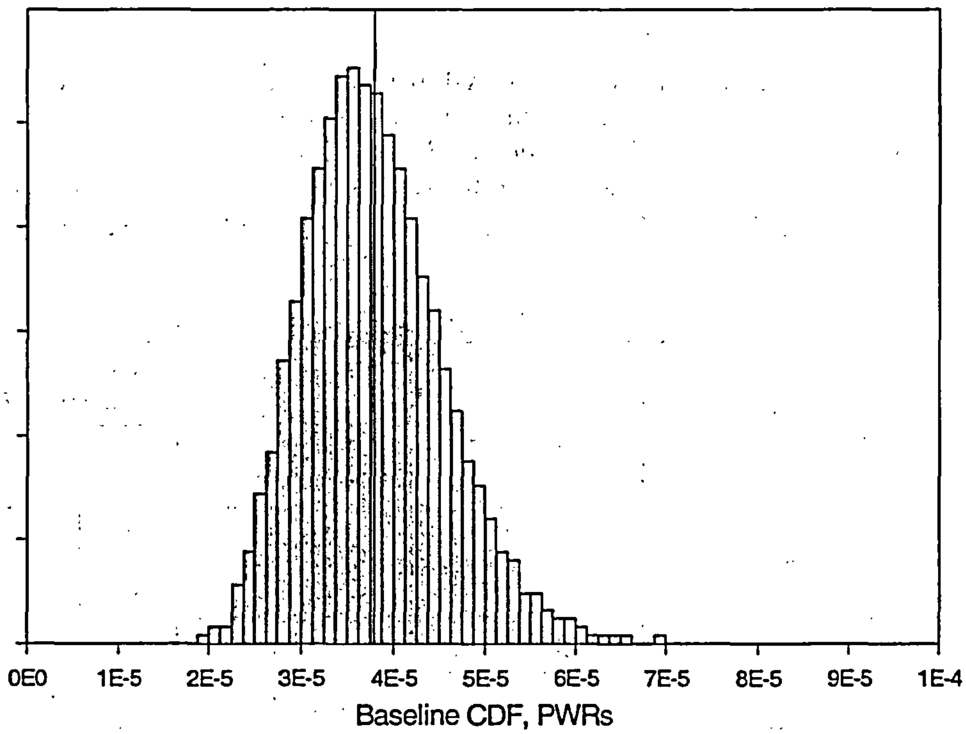

Figure A-1 Baseline CDF for PWRs, including uncertainty in λ_i values.

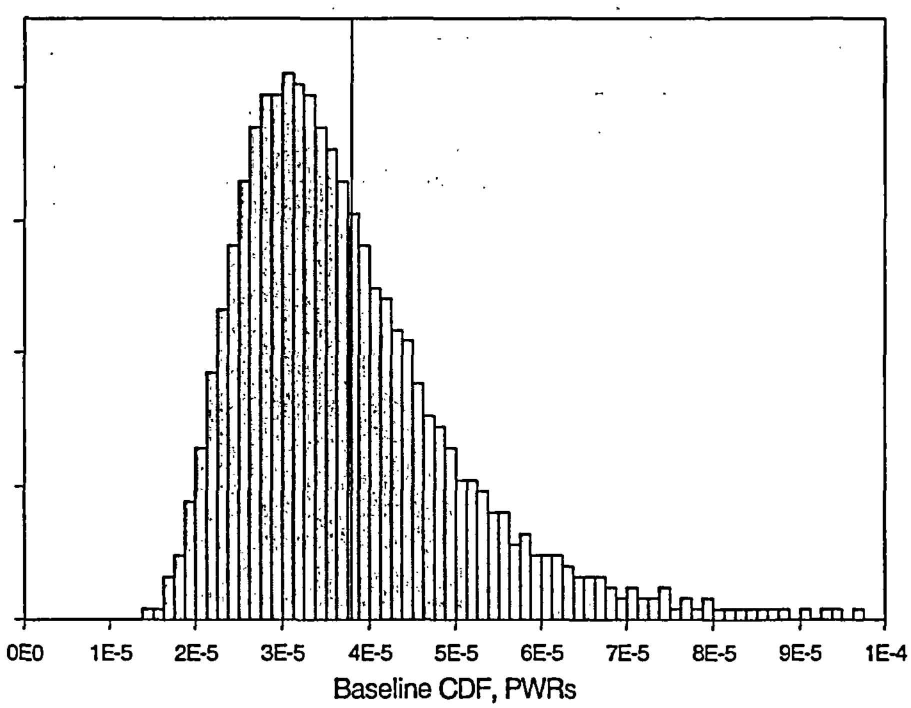

Figure A-2 Baseline CDF for PWRs, including uncertainty in λ_i values and in Birnbaum importances.

A.3.1 BWR Baseline CDF

Table A-2 shows the same information as Table A-1, but now for BWRs. Figures A-3 and A-4 show the uncertainty distributions, respectively excluding or including uncertainty in the Birnbaum importances. The 5th and 95th percentiles of the distributions are 8.88×10^{-6} and 1.58×10^{-5} when only uncertainty in the λ_i values is considered, and 7.18×10^{-6} and 1.93×10^{-5} when the uncertainty in the Birnbaum importances is also considered. The mean is 1.20×10^{-5} in any case. The units are events per reactor-critical year in every case.

Table A-2 Breakdown of BWR Baseline CDF by Initiating Event

Initiating Event	Mean of Baseline CDF		Variance, without Birnbaum Uncertainty		Variance, Including Birnbaum Uncertainty		Baseline Prior, Gamma(a, b)		Mean Birnbaum Importance
							a	b	
LOSP	5.50E-6	46%	4.03E-12	89%	1.35E-11	85%	7.5	4.39E+2	3.22E-4
BWR_Sink	1.60E-6	13%	7.69E-14	2%	5.04E-13	3%	33.5	1.76E+2	8.44E-6
Feedwater	1.49E-6	12%	2.74E-14	1%	6.04E-13	4%	80.5	7.85E+2	1.45E-5
BWR_Trans	1.22E-6	10%	1.13E-14	0%	4.54E-13	3%	131.5	1.47E+2	1.36E-6
BWR_SRV	1.00E-6	8%	1.83E-13	4%	3.78E-13	2%	5.5	2.58E+2	4.71E-5
DC_Bus	7.99E-7	7%	1.83E-13	4%	3.50E-13	2%	3.5	1.18E+3	2.70E-4
SLOCA	2.61E-7	2%	1.24E-14	0%	6.38E-14	0%	5.5	1.18E+3	5.62E-5
BWR_Air	8.85E-8	1%	3.14E-15	0%	1.20E-14	0%	2.5	2.32E+2	8.20E-6
Total	1.20E-5	100%	4.53E-12	100%	1.58E-11	100%			

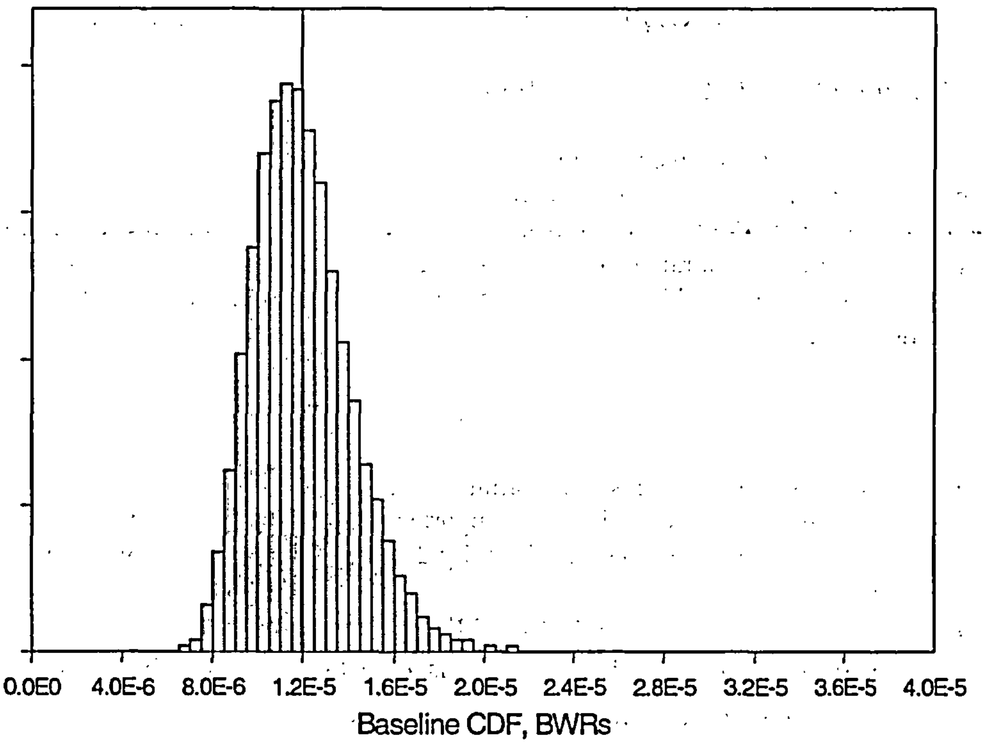

Figure A-3 Baseline CDF for BWRs, including uncertainty in λ_i values.

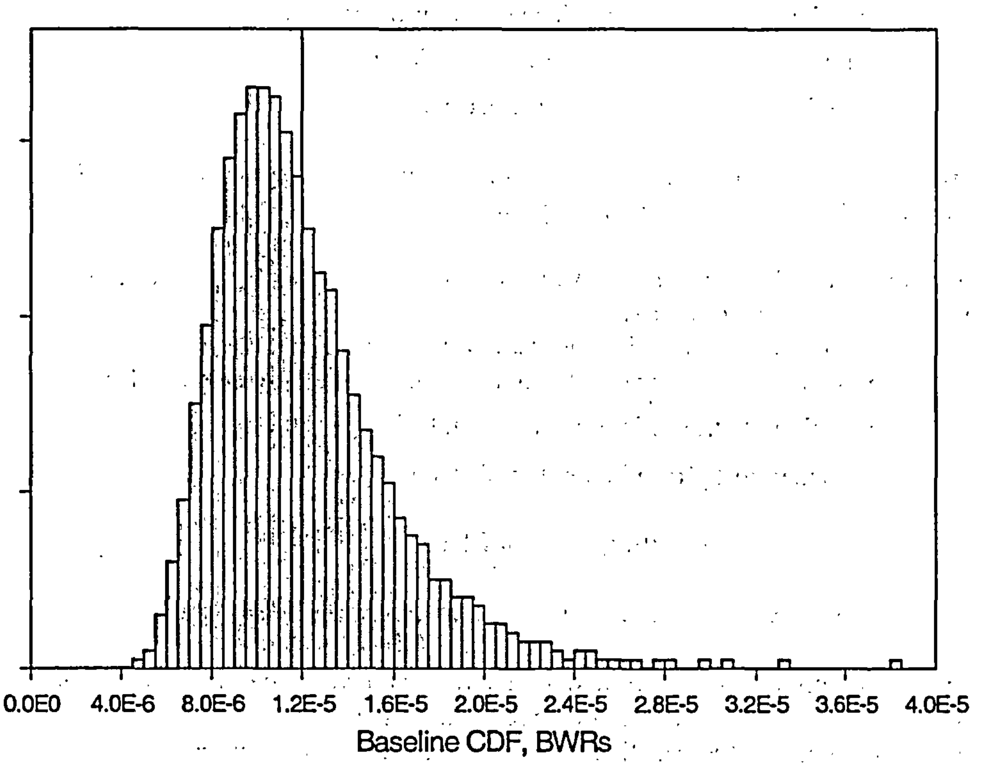

Figure A-4 Baseline CDF for BWRs, including uncertainty in λ_i values and in Birnbaum importances.

A.4 PREDICTIVE DISTRIBUTION FOR BRIIE

A.4.1 Definition of Predictive Distribution

BRIIE is an estimate of ΔCDF given by Equation A-2, 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 A.2. The indicator is a random variable — different data counts result in different values of BRIIE. Equation A-2 is repeated here with slightly different notation, and with all the uncertainties and random variation are explained.

$$BRIIE = \sum_{i=1}^{m} B_i(\lambda_i^* - \lambda_{i,base}^*)$$

where

- m is the number of types of initiating event
- B_i is an estimate of the Birnbaum importance of the ith type of initiating event. It is random, depending on the reliability data that form the basis of the cutset probabilities in the SPAR model.
- λ_i is the true, unknown frequency of the ith type of initiating event.
- $\lambda_{i,base}^*$ is the estimate of the baseline λ_i. It is a function of the baseline data ($X_{i,base}$, $t_{i,base}$). The distribution of $X_{i,base}$ depends on the unknown λ_i.
- λ_i^* is the estimate of the current or future λ_i. It is based on the current or future data (X_i, t_i) and therefore is random. The distribution of X_i depends on the unknown λ_i. When the Bayesian methodology is used, the prior depends on $\lambda_{i,base}^*$, so the current estimate is also dependent on the baseline estimate.

It is important to note the following: for the work of this section, we assume that λ_i is the same in the baseline period and in the current or future period.

The distribution that includes all the above uncertainty and variability can be simulated as follows.

1. For each i from 1 to m:
   - Generate λ_i from its uncertainty distribution.
   - Generate $X_{i,base}$ and X_i from their Poisson distributions conditional on λ_i.
   - Calculate the estimates $\lambda_{i,base}^*$ and λ_i^*.
   - Generate B_i from its random distribution.
2. Calculate the resulting value of BRIIE.
3. Repeat Steps 1 and 2 many times, getting many values of BRIIE.

The above distribution has mean zero and a relatively large variance. However, it is not fully relevant to the present work. It uses data "that might have been," when some of the data values (the estimated Birnbaum importances and the baseline data) have already been observed.

The more relevant distribution is the **predictive distribution**, which is the distribution conditional on the data that have already been observed: the data that give B_i and $\lambda^*_{i,base}$. When this conditional distribution is used, B_i and $\lambda^*_{i,base}$ are treated as known data values, and the uncertainty distribution of λ_i is conditional on the known baseline data. This conditional distribution is the posterior distribution of λ_i given $x_{i,base}$ and $t_{i,base}$. The predictive distribution of BRIIE can be simulated as follows.

First, one must do some preliminary work for each *i* from 1 to *m*. Use the Jeffreys noninformative prior, 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}). As a slight digression, we can note that the baseline distributions of Figures A-1 and A-3 are obtained by assigning these posterior distributions to the parameters λ_i in Equation A-1. Set $\lambda^*_{i,base}$ to the mean of this posterior distribution,

$$\lambda^*_{i,base} = \frac{x_{i,base} + 0.5}{t_{i,base}}$$

Also, for each *i*, obtain B_i from the SPAR model. Now perform the simulation:

1. For each *i* from 1 to *m*:
   - Generate λ_i from its posterior distribution.
   - Generate X_i from its Poisson distribution conditional on λ_i.
   - Calculate the estimate λ_i^*.

2. Calculate the resulting value of BRIIE.

3. Repeat Steps 1 and 2 many times, obtaining many values from the predictive distribution of BRIIE.

This process generates the predictive distribution for each X_i. This predictive distribution is discussed more fully by Atwood (2002), where it is advocated over several other possible definitions of predictive distributions. When they are combined to produce BRIIE, the result is the predictive distribution for BRIIE.

The conditional mean of λ_i^* is $\lambda^*_{i,base}$. Therefore, the conditional mean of BRIIE is zero.

The histograms below are obtained in this way, simulating 200,000 values of BRIIE 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 are indicative of a change in the process.

A.4.2 Predictive Distribution of BRIIE for PWRs

The predictive distribution is shown for PWRs. Figure A-5 assumes that each λ_i is estimated by the Bayes estimate, and Figure A-6 assumes that each λ_i is estimated by the maximum likelihood estimate. The data window equals one industry year (61.72 PWR-critical years, 93.49 overall reactor-critical years) in each case.

The multimodal nature of the figures, especially Figure A-6, is a result of BRIIE being very sensitive to two kinds of very rare initiating events, small LOCA and loss of DC bus, as seen in Table A-1. The first bump corresponds to the occurrence of no such events in the year of data, the second bump corresponds to the occurrence of one such event, the third to two such, and so forth. Figure A-5 is smoother, and it has a smaller variance. Both features are a consequence of using a Bayesian prior distribution.

For most of this report, the Bayesian estimator is used, corresponding to Figure A-5. The 95th and 99th percentiles of this distribution in Figure A-5 are 2.21E-5 and 3.54E-5.

The above distributions ignore the uncertainty in the Birnbaum importances, for reasons given in Section A.4.1. However, Figure A-7 shows the cumulative predictive distribution of BRIIE using Bayesian estimates, when the uncertainty in Birnbaum importances is excluded and included, respectively. The two curves in Figure A-7 are very similar except in the lower tail. This shows that there is little advantage to accounting for the Birnbaum uncertainties, and two disadvantages. One disadvantage is a conceptual one, discussed in Section A.4.1. The other disadvantage of using uncertainty for the Birnbaum importances is that it is difficult to quantify them exactly. The values here are rough approximations.

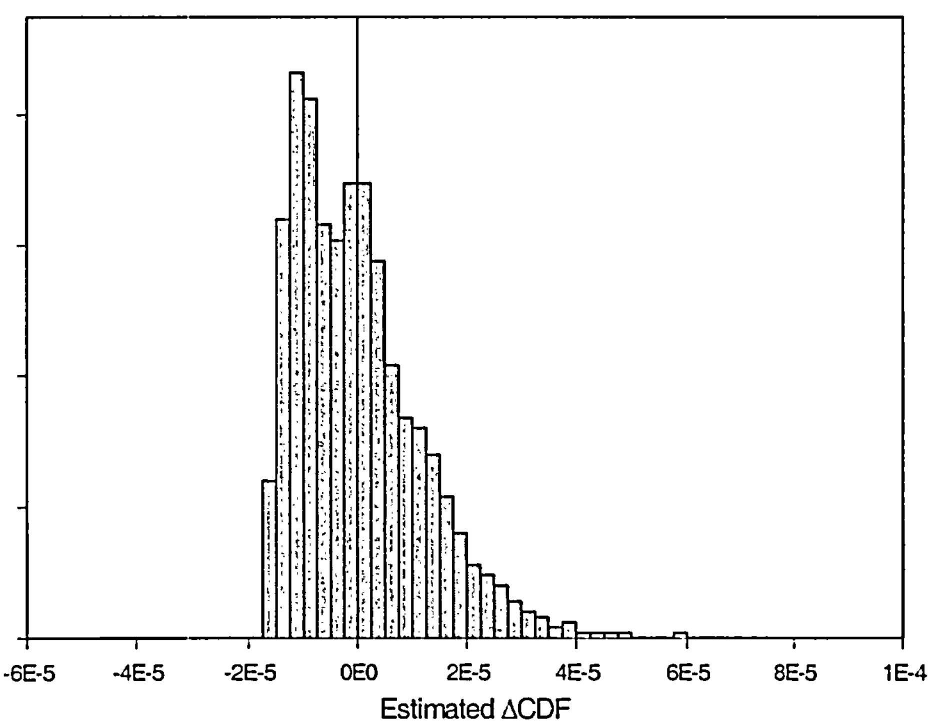

Figure A-5 Predictive distribution of BRIIE for PWRs, when Bayesian estimators are used with one year of data to estimate frequencies.

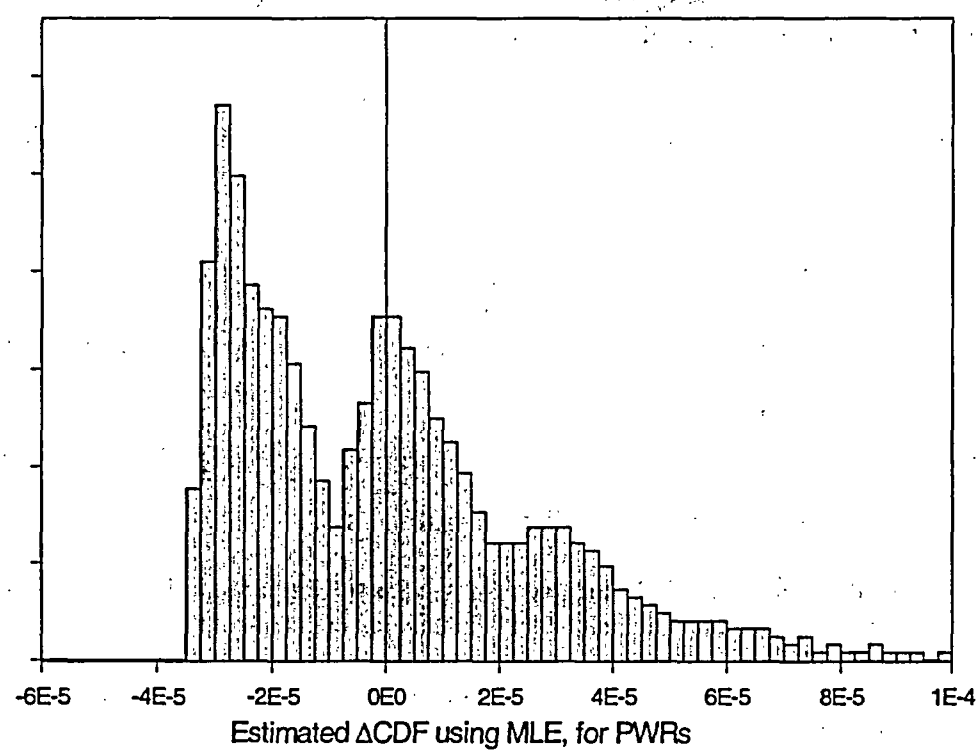

Figure A-6 Predictive distribution of BRIIE for PWRs, when MLEs are used with one year of data to estimate frequencies.

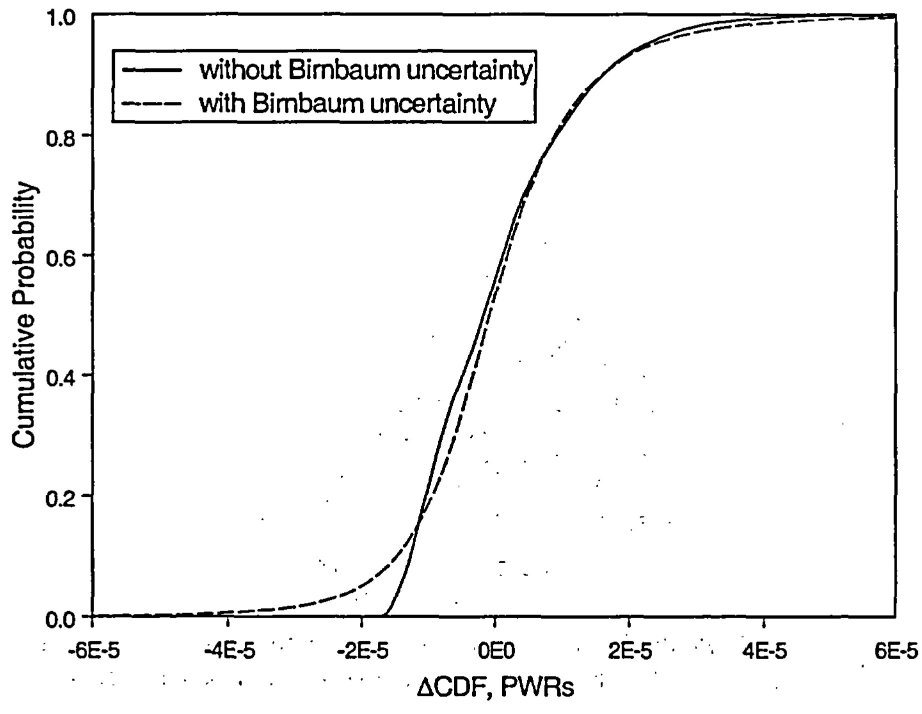

Figure A-7 Cumulative predictive distribution for BRIIE, and distribution that includes uncertainty in Birnbaum importances.

A.4.3 Predictive Distributions of BRIIE for BWRs

Figures A-8 and A-9 show the predictive distribution of BRIIE for BWRs,when each λ_i is estimated by Bayesian estimate or by the maximum likelihood estimate x_i/t_i, and the current data window contains one industry year of data.

Neither figure shows the strong multimodality seen in Figure A-6. However, Figure A-8 shows a smaller variance that Figure A-9. This is neither an advantage nor a disadvantage; it is just a feature that results from using a Bayes prior distribution. For most applications of this report, the Bayesian version will be used, corresponding to Figure A-8. The 95th and 99th percentiles of that distribution are 7.24E-6 and 1.14E-5.

A figure analogous to Figure A-7 is not shown, because qualitatively it is very similar to Figure A-7.

A.4.4 Final comments Regarding Predictive Distributions

For all the above calculations, a BWR industry year was assumed to equal 31.77 reactor-critical-years, and a PWR industry year was assumed to equal 61.72 reactor-critical-years. These were the values actually observed in FY 2001, the last year of the baseline periods. They differed only slightly from the critical years in 2002. If any year should occur with quite different reactor-critical years (for example, if several reactors are shut down for an extended period), the assumed exposure times should be adjusted.

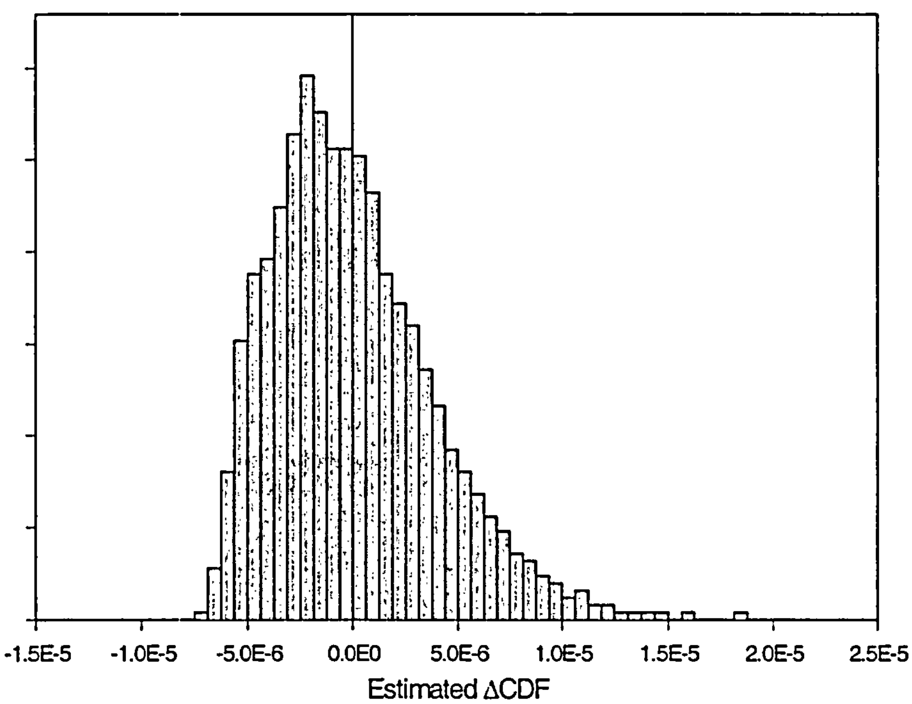

Figure A-8 Predictive distribution for BRIIE for BWRs, when Bayesian estimators are used with one year of data to estimate frequencies.

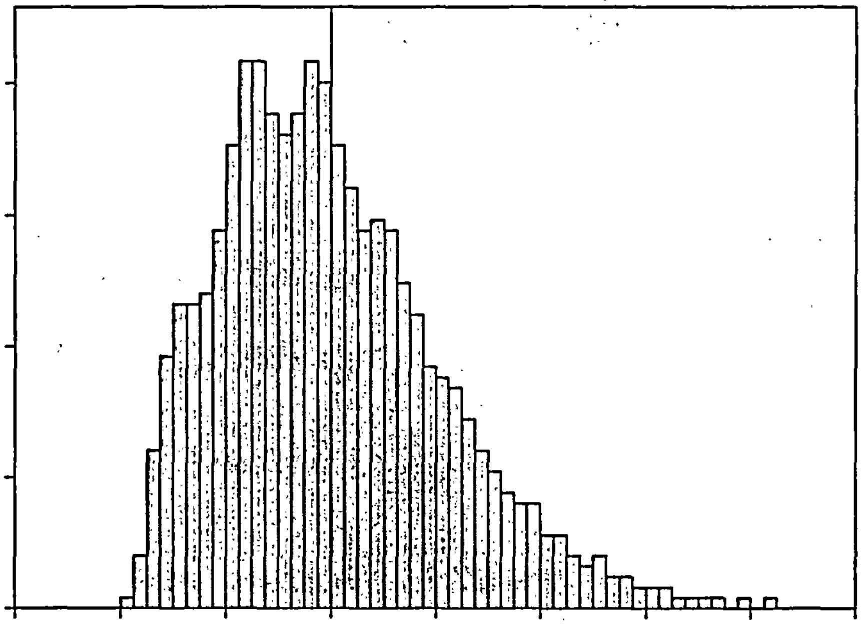

Figure A-9 Predictive distribution for BRIIE for BWRs, when MLEs are used with one year of data to estimate frequencies.

A.5 SENSITIVITY OF BRIIE TO NON-BASELINE CONDITIONS

The distribution of BRIIE was simulated to see how successful BRIIE was at detecting off-baseline situations. The figures below show the cumulative distribution of BRIIE under three assumptions. The first is that the initiating-event frequencies are at their baseline values. The resulting distribution is the predictive distribution shown earlier. The second assumption is that the initiating-event frequencies are all at 1.5 times the baseline means. The third assumption is that the initiating-event frequencies are all at 2 times the baseline means.

A possible threshold for action is the 95th percentile of the baseline predictive distribution. This value is shown as a vertical dotted line in the plots. As can be seen in the figures, the distribution of BRIIE is shifted to the right under the assumed non-baseline conditions. However substantial portions of the distribution still remain to the left of the 95th percentile of the baseline predictive distribution.

It is also evident from the plots that BRIIE is somewhat more successful at detecting non-baseline conditions for BWRs than for PWRs.

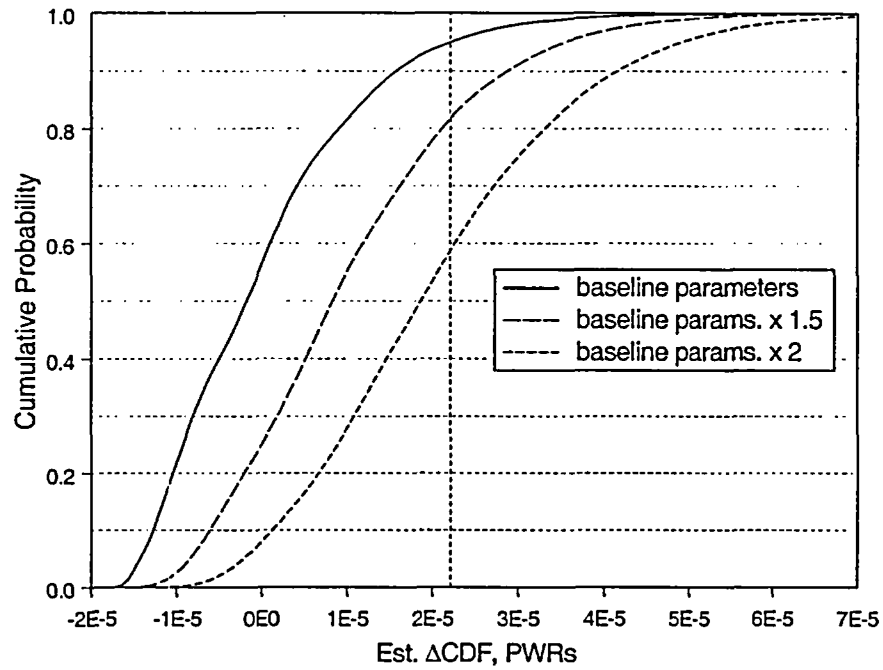

Figure A-10 Cumulative distribution of BRIIE for PWRs under three assumptions: all initiating-event frequencies at baseline, or at 1.5 times baseline, or at 2 times baseline. The vertical line is the 95th percentile of the baseline distribution.

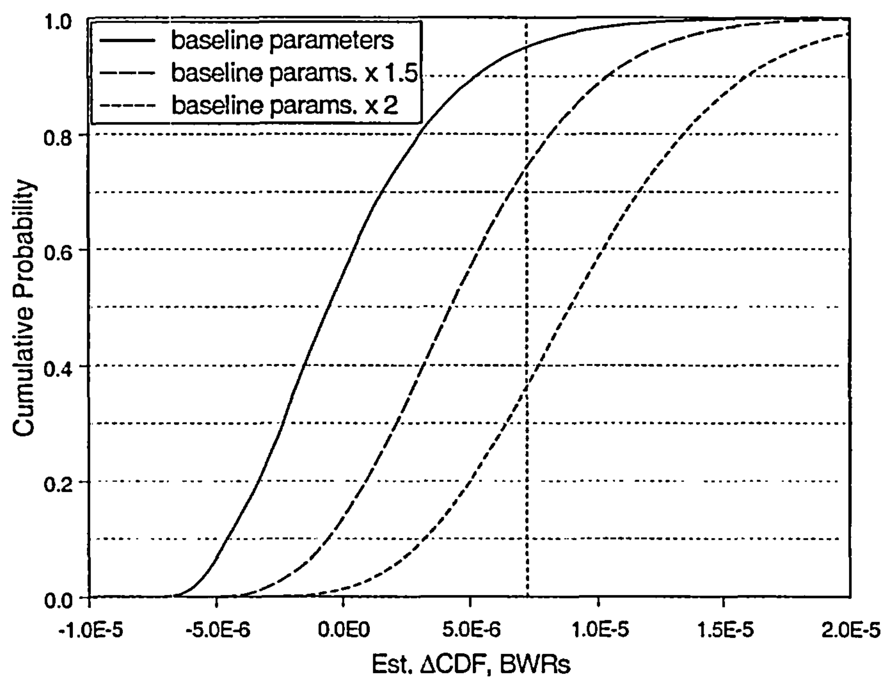

Figure A-11 Cumulative distribution of BRIIE for BWRs under three assumptions: all initiating-event frequencies at baseline, or at 1.5 times baseline, or at 2 times baseline. The vertical line is the 95th percentile of the baseline distribution.

A.6 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.

A.6.1 Variation of Birnbaum Importances Among PWRs

The plant-specific baseline CDF is shown in Figure A-12. This is calculated using Equation (A-1), with a single frequency for each kind of initiating-event, applicable at all plants, and plant-specific Birnbaum importances. Uncertainties in the frequencies are not shown. The figure includes the 60 PWRs with SPAR models as of the Summer 2002. Since then, SPAR models have been completed for all 69 PWRs. Birnbaum importances for the remaining 9 plants have not been added to this study.

The outlying values on the right correspond to the two units at a single station, having a single SPAR model. The next smallest values, approximately 8×10^{-5}, correspond to two other two-unit stations. From Table A-1, 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 A-13 and A-14. The outlying plants for Small/Very Small LOCA are the most extreme two plants in Figure A-12. The outlying plants for Loss of Vital DC Bus are the next four most extreme plants in Figure A-12.

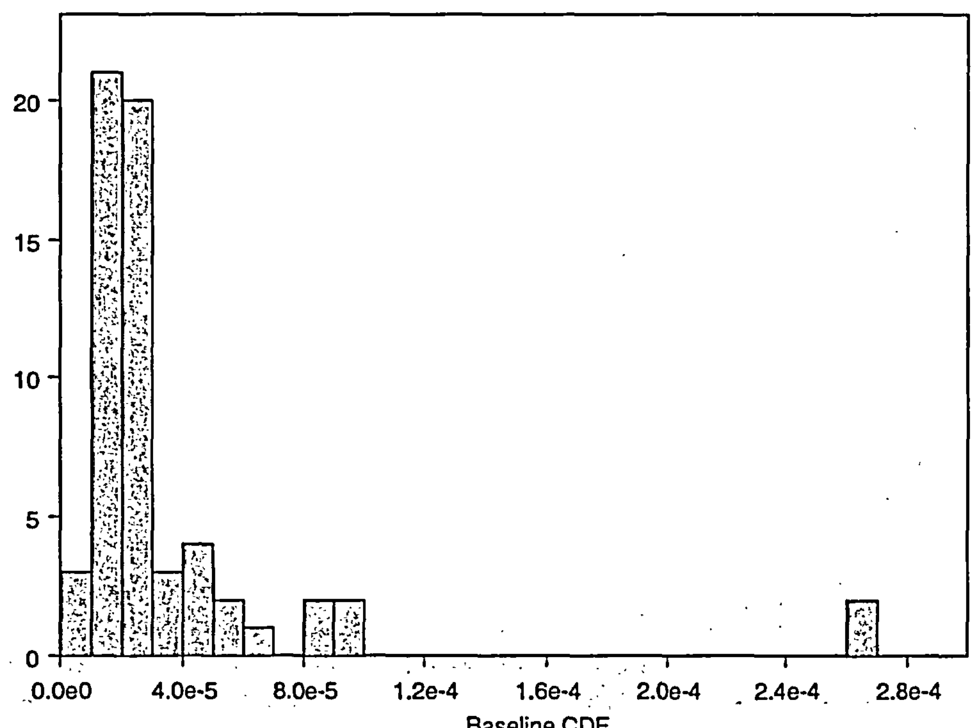

Figure A-12 Baseline CDF at 60 PWRs.

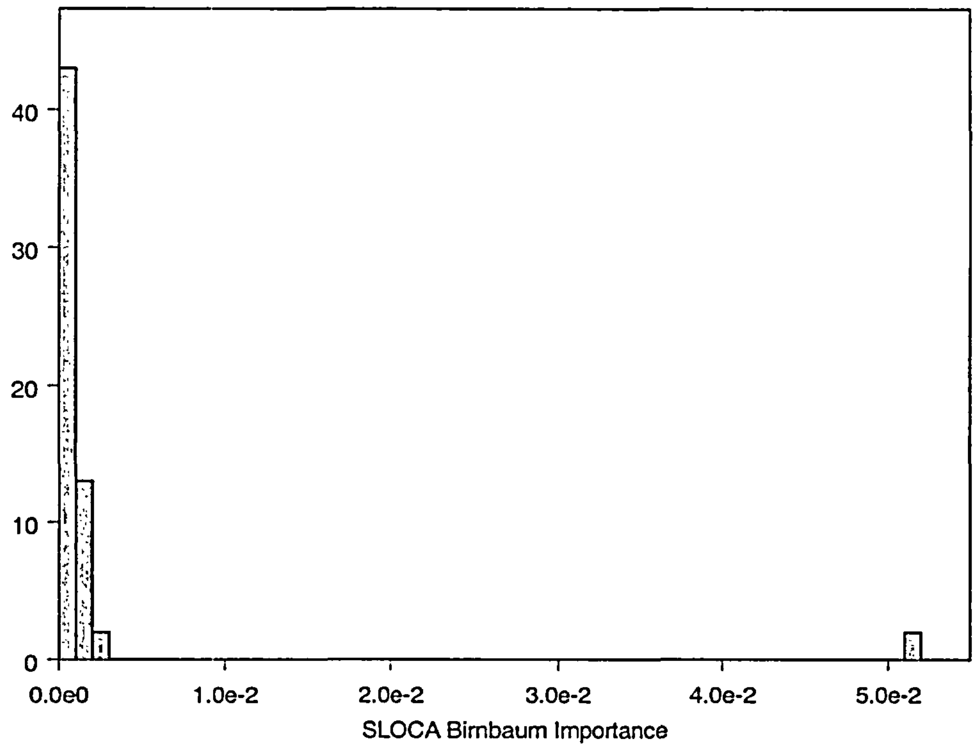

Figure A-13 Birnbaum importance of Small/Very Small LOCA at 60 PWRs.

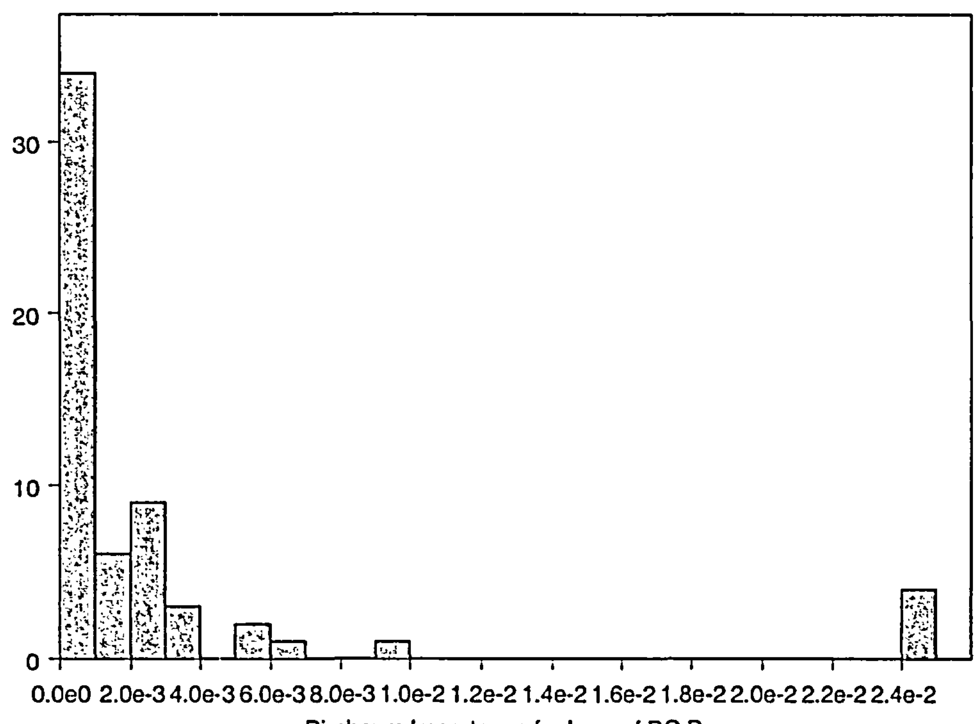

Figure A-14 Birbaum importance of Loss of Vital DC Bus at 60 PWRs.

A.6.2 Variation of Birnbaum Importances Among BWRs

The plant-specific baseline CDF for BWRs is shown in Figure A-15. This is calculated using Equation A-1, with a single frequency for each kind of initiating-event, applicable at all plants, and plant-specific Birnbaum importances. This figure includes the 32 BWRs with SPAR models as of the Summer 2002. Since then, SPAR models have been completed for all 34 BWRs. Birnbaum importances for the remaining two plants have not been added to this study.

As shown in Table A-2, the dominant initiating event for BWRs is Loss of Offsite Power (LOOP). Therefore, it can be expected that the most extreme plant in Figure A-13 has an outlying Birnbaum importance for LOOP. In Figure A-16, the extreme value on the right corresponds to a single BWR, the same plant in both figures. The match between Figures A-15 and A-16 breaks down for the other plants–the second largest plant in Figure A-15 is different from the second largest plant in Figure A-16.

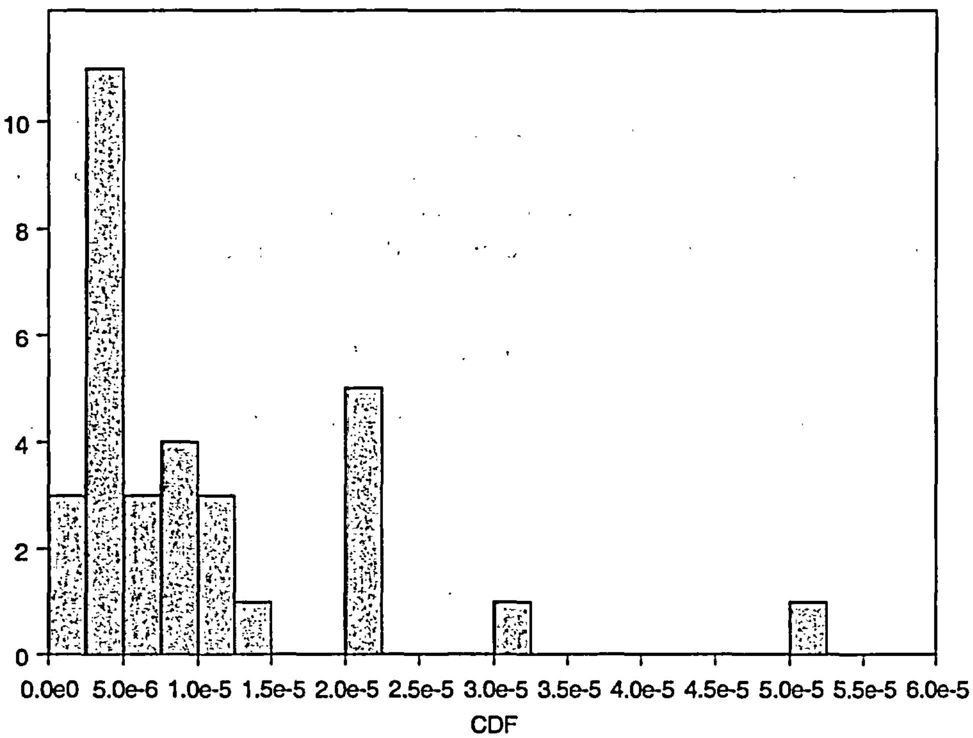

Figure A-15 Baseline CDF at 32 BWRs.

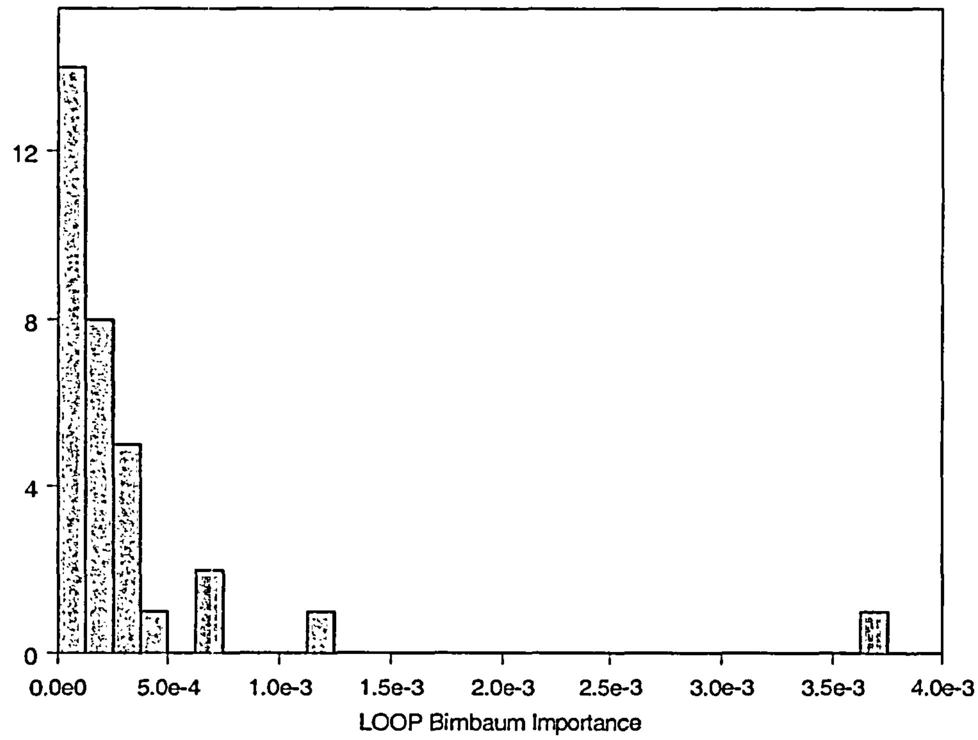

Figure A-16 Birnbaum importance of LOOP at 32 BWRs.

A.7 REFERENCE

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

APPENDIX B

Initiating Event Birnbaum Importance Measures

INITIATING EVENT BIRNBAUM IMPORTANCE MEASURES

The Baseline Risk Index for Initiating Events (BRIIE) requires Birnbaum importance measures for each of 10 types of initiating events. 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 early 2004. When all of the Rev. 3i models have been converted to Rev. 3 models, the Birnbaum estimates should be revised.

The BRIIE 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 BRIIE 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 B-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 B-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:

1. Initiating event frequencies,
2. Basic event failure probabilities,
3. Treatment of loss of offsite power,
4. Treatment of steam generator tube rupture, and
5. Human reliability failure probability estimates.

Table B-1 Initiating event industry-average Birnbaum importance measures

Initiating Event	Birnbaum Importance[a]		Initiator Modeled Explicitly in SPAR?	Birnbaum Importance Obtained How?	Comments
	BWRs	PWRs			
General Transients	1.36E-6	2.02E-6	Yes[b]	Cut set slicing	
Loss of Heat Sink	8.44E-6	1.89E-5	No	Cut set slicing	
Loss of Feedwater	1.45E-5	1.89E-5	No	Cut set slicing	
Loss of Offsite Power	3.22E-4	3.25E-4	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).
Stuck Open SRV	4.71E-5	6.36E-4	No	Cut set slicing	
Loss of Instrument Air	8.20E-6	8.35E-5	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).

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.