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GSI-191: The Impact of Debris-Induced Loss of ECCS Recirculation on PWR Core Damage Frequency

Technical Letter Report

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EXECUTIVE SUMMARY

Recent research supporting resolution of Generic Safety Issue (GSI) 191, "Assessment of Debris Accumulation on PWR Sump Performance," has identified a range of conditions in which pressurized water reactor (PWR) emergency core cooling systems (ECCS) could fail in the recirculation mode of operation.[1] These conditions stem from the destruction and suspension of piping insulation materials, containment surface coatings (paint), and particulate matter (e.g., dirt) by the steam/water jet emerging from a postulated break in reactor coolant piping. Under certain circumstances, this debris can be transported to the floor of the containment and accumulate on the recirculation sump screen in sufficient quantity to severely impede recirculation flow. The likelihood that these conditions could occur during a postulated loss-of-coolant accident (LOCA) is plant-specific. However, a review of the design features for U.S. PWRs conducted as part of the GSI-191 research clearly indicates that adverse conditions exist in several plants.

This report examines the risk significance of these findings. Specifically, the goal is to estimate the amount by which core damage frequency (CDF) would increase if failure of PWR ECCS recirculation cooling as a result of debris accumulation on the sump screen were accounted for in a manner that reflects the results of recent experimental and analytical work. This estimate is to be made in a manner that reflects the ***total population*** of U.S. PWRs; i.e., it should provide information appropriate for use in the resolution of the GSI.

The CDF analysis was accomplished using conventional probabilistic risk assessment (PRA) tools, such as accident-sequence event trees. The event trees were constructed and quantified at a functional level but included sufficient detail to account for major differences in plant design features that affect the requirement for suction flow from the containment sump, including alternative nuclear steam supply system (NSSS) designs and containment types. For example, subatmospheric containment designs do not incorporate heat removal in the ECCS system; however, heat removal is required for successful containment spray recirculation. The analysis was conducted in a manner that directly parallels the deterministic evaluations of sump performance described in the companion study to this work. That is, the effect of debris-induced recirculation sump failure on CDF was evaluated for 69 distinct cases, representing the entire population of U.S. PWRs.

The results suggest that the conditional probability of recirculation sump failure (given a demand for recirculation cooling) is sufficiently high at many U.S. plants to cause an increase in the total CDF of an order of magnitude or more. As illustrated in Figure ES.1, the factor by which the total core damage would increase if debris-induced recirculation sump failure were included in PWR PRA models spans the range of 1.0 (i.e., no change) to 90, with an average of approximately 45.[2] However, it is important to note that these results do not take into account the possibility that ECCS pumps might continue to function with loss of net positive suction head (NPSH) margin or that operators can take manual actions to restore core cooling if normal recirculation flow terminates. Such considerations are highly pump-design specific and plant-specific, respectively, and beyond the scope of this study.

The contribution of each type of accident sequence to the estimated CDFs is indicated in Table ES.1. This table lists the baseline and modified CDF associated with each of the accident sequences considered in this analysis, averaged over the entire population of U.S.

[1] The results of this research are described in a companion report titled "GSI-191: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance."

[2] The results in Figure ES.1 are plotted in the form of the ratio of the CDF including effects of debris generation and accumulation on sump screen to the baseline CDF, which does not account for these effects. These values are generated using LOCA initiating-event frequencies that account for leak before break; a wider range is obtained when LOCA initiating-event frequencies are based on traditional initiating-event databases. The results using both frequencies are presented in the full report.

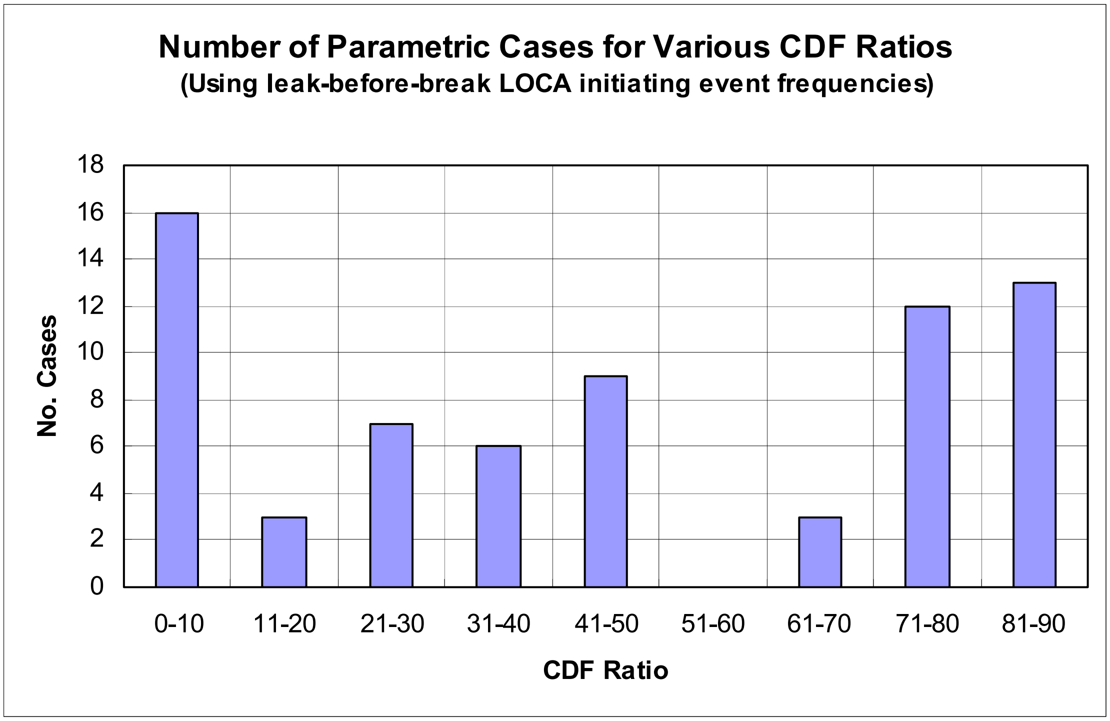

Figure ES.1 Effect of Debris-Induced Loss of Recirculation Sump Flow on CDF Expressed in Terms of CDF Ratio: Modified CDF/Baseline CDF

Table ES.1 Contributions of Each Accident Sequence to the Baseline and Modified CDF[3]

	Large LOCA	Medium LOCA	Small (S3) LOCA	Very Small (S2) LOCA	PORV	LOFW	TOTAL
With debris	2.9E-06	1.0E-05	5.8E-06	1.2E-04	9.6E-06	8.5E-07	1.5E-04
No debris	2.6E-08	1.1E-07	2.4E-08	4.8E-07	2.2E-06	4.2E-07	3.3E-06
ΔCDF	2.9E-06	9.9E-06	5.7E-06	1.2E-04	7.4E-06	4.3E-07	1.5E-04
CDF ratio	113	87	236	243	4	2	45

[3]These values represent the arithmetic average of the sequence CDF for each of 69 cases. The values are based on leak-before-break values for LOCA initiating-event frequencies; a wider range is obtained when LOCA initiating-event frequencies are based on traditional initiating-event frequency databases. The results using both frequencies are presented in the full report.

PWRs.[3] Two observations can be made from this table. First, LOCA events dominate the estimated *increase* in CDF [i.e., stuck-open power-operated relief valve (PORV) and loss-of-feedwater events are not significantly affected by the issue]. Second, the largest increase in CDF (measured by CDF ratio) occurs in small-break LOCAs. It should be noted that small break LOCAs are also events in which recovery actions are most likely to be effective, and thus, more detailed plant-specific evaluations are likely to show much smaller increases in CDF for these sequences.

An examination of the major contributors to the estimated increase in CDF indicates that no *single* plant design feature is responsible for a large conditional probability of failure. Conversely, no *single* design feature safeguards a plant from the potential for excessive debris-induced head loss. These findings underscore the need for plant-specific analysis to characterize recirculation sump performance.

[3] These values represent the arithmetic average of the sequence CDF for each of 69 cases. The values are based on leak-before-break values for LOCA initiating-event frequencies; a wider range is obtained when LOCA initiating-event frequencies are based on traditional initiating-event frequency databases. The results using both frequencies are presented in the full report.

ABBREVIATIONS

CDF	Core Damage Frequency
CE	Combustion Engineering
ECCS	Emergency Core Cooling System
FTDL	Failure Threshold Debris Loading
GSI	Generic Safety Issue
HHSI	High-Head Safety Injection
HHSR	High-Head Safety Recirculation
HPSI	High-Pressure Safety Injection
IPE	Individual Plant Examination
LOCA	Loss-of-Coolant Accident
LLOCA	Large LOCA
LANL	Los Alamos National Laboratory
LHSI	Low-Head Safety Injection
LHSR	Low-Head Safety Recirculation
LOFW	Loss of Feedwater
LPSI	Low-Pressure Safety Injection
MLOCA	Medium LOCA
NPSH	Net Positive Suction Head
NRC	Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
PORV	Power-Operated Relief Valve
PRA	Probabilistic Risk Assessment
PWR	Pressurized Water Reactor
RCP	Reactor Coolant Pump
RHR	Residual Heat Removal
RWST	Refueling Water Storage Tank
SDC	Shutdown Cooling
SLOCA	Small LOCA
SLOCA-1	Size-1 Small LOCA
SLOCA-2	Size-2 Small LOCA
SLOCA-3	Size-3 Small LOCA
SSC	Systems, Structures, & Components
TRAN-PORV	Transient with a Stuck-Open PORV
TRAN-LOFW	Transient with a Loss of Feedwater
UFSAR	Update Final Safety Analysis Report

1.0 INTRODUCTION

Recent research supporting resolution of Generic Safety Issue (GSI) 191, "Assessment of Debris Accumulation on Pressurized Water Reactor (PWR) Sump Performance," has identified a range of conditions in which PWR Emergency Core Cooling Systems (ECCS) could fail in the recirculation mode of operation.[4] These conditions stem from the destruction and suspension of piping insulation materials, containment surface coatings (paint), and particulate matter (e.g., dirt) by the steam/water jet emerging from a postulated break in reactor coolant piping. Under certain circumstances, this debris can be transported to the floor of the containment and accumulate on the recirculation sump screen in sufficient quantity to severely impede recirculation flow. The likelihood that these conditions could occur during a postulated loss-of-coolant accident (LOCA) is plant-specific. However, a review of the design features for U.S. PWRs conducted as part of the GSI-191 research clearly indicates that adverse conditions exist in several plants.[1]

The specific mechanism by which these phenomena can lead to ECCS recirculation failure is a loss of adequate net positive suction head (NPSH) margin; i.e., debris-induced flow resistance across the sump screen results in a condition where the NPSH required for successful pump operation exceeds the NPSH available. To date, this failure mode has not been addressed explicitly in plant-specific or generic probabilistic risk assessments (PRAs) performed in the U.S because, until recently, the phenomenon was not considered credible. This report provides an estimate of the extent to which estimated core damage frequencies (CDFs) would change if the probability of this failure mode were added to typical PWR PRA models and were quantified based on the results of the recent GSI-191 research.

1.1 Objective

The primary objective of the work described in this report is to determine the risk significance of the findings described in the companion report "GSI-191: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance" [1]. Specifically, the goal is to estimate the amount by which CDF would increase if failure of (PWR) ECCS recirculation cooling as a result of debris accumulation on the sump screen were accounted for in a manner that reflect results of recent experimental and analytical work. This estimate is to be made in a manner that reflects the ***total population*** of U.S. PWRs; i.e., it should provide information appropriate for use in the resolution of the GSI.

1.2 Approach

The parametric evaluations of recirculation sump performance examined potential quantities of LOCA-generated debris and ECCS recirculation sump design characteristics for the entire population of U.S. PWRs. Plant-specific information was used to address major differences in the design features among 69 operating plants. However, plant-specific information was not available for all parameters of interest to the study. In situations where information could not be obtained from resources readily available to the NRC and its contractors, generic information was used.

A similar approach was adopted to estimate the effect of debris-induced loss of NPSH margin on CDF. The approach centers on a generic PRA model for the most common plant design: a Westinghouse four-loop PWR with a large dry containment. This model provides a common framework for delineating the accident sequences in which loss of recirculation flow could lead to core damage. Major differences in plant design features that affect the requirement for suction flow from the containment sump were also included in the model, including alternative nuclear steam supply system (NSSS) designs and containment types. For example, subatmospheric containment designs do not incorporate heat removal in the ECCS system; however, heat removal is required for successful containment spray recirculation.

The CDF analysis was performed using conventional event-tree models. An event tree graphically displays the possible paths that an

[4] Detailed results of this research are described in a draft report published by Los Alamos National Laboratory (LANL) [1].

accident may take following an initiating event. The event tree lays out, in chronological order, the plant systems and operator actions that would be called on to respond to the initiating event. "Branches" in the event tree represent alternative responses of a particular system (or operator action); i.e., successful actuation and operation of a coolant injection system or failure to operate as required. Therefore, each path through the event tree represents a unique string of successful or failed mitigating feature responses to a prescribed initiating event and thus defines an accident sequence.

In a complete PRA, the events incorporated in a fully developed event tree can be quite extensive and reflect detailed aspects of system operations. Supporting fault trees typically include logic to reflect the interdependency of front-line systems and support systems, such as electric power, component cooling water, etc. This level of detail is simply impractical to include in a generic model that can be applied to represent the response of the entire population of U.S. PWRs. As a result, the event-tree models used in this analysis represent the mitigating features from a functional standpoint. That is, a "failure" branch on the event tree representing (for example) "ECCS Operation in Injection Mode" simply represents a plant state in which ECCS injection does not operate when required. Specific causes of the loss of ECCS injection cannot be derived from the analysis; rather, representative failure rates for the *overall function* of core coolant makeup are applied to the model.

Although this level of detail is not sufficient for many PRA applications, it does provide an adequate foundation for an assessment of the effect of debris-induced loss of ECCS recirculation. A precise estimate of the CDF is not necessary for such an application. Rather, one only requires a physically sound delineation of the accident sequences in which the suction flow from the recirculation sump would be demanded and a representative estimate of the frequency of such sequences. This estimate provides a "baseline" estimate of PWR CDF for various classes of accident scenarios; i.e., large LOCA (LLOCA), small LOCA (SLOCA), etc. Estimates of the effect of sump unavailability on CDF then are made by adding new events to the baseline event trees that represent the deleterious effects of debris accumulation on the sump screen. Therefore, the CDF contribution resulting solely from such effects is represented by the difference in the total CDF reflected in the baseline and expanded models.

To implement this approach, a series of baseline event trees was developed for several types of accidents (i.e., initiating events). A description of the accident selected for analysis is provided in Sec. 2.0; descriptions of the corresponding event trees are provided in Sec. 3.0. Three new events were added to the event trees for each initiating event to address the effect of debris in the sump.

(a) Avoid Loss ECCS Recirculation NPSH Margin due to Debris
(b) ECCS Recirculation with Loss NPSH Margin
(c) Recover from Loss of ECCS Recirculation due to Debris

The first event accounts for the conditional probability that the NPSH margin is lost as a result of excessive debris accumulation on the sump screen. The probability is dependent on the state of the plant systems for a specific accident sequence (i.e., the number of ECCS pumps running to accommodate coolant losses through a break of a given size) and is based on the debris phenomena for the specific accident sequence. The conditional probabilities for loss of the recirculation sump as a result of LOCA-induced debris are based on results described in "Parametric Evaluations for PWR Sump Performance," the companion report to this assessment [1]. The specific method used to translate the results in the parametric evaluations to values for failure probability is described in Sec. 4.0 of this report.

It is possible that pump(s) can operate in a degraded mode with loss of NPSH margin; the event "ECCS Recirc with Loss of NPSH Margin" accounts for this possibility. This event is included in the event tree used for this study, but it is not quantified because of a lack of data on pump performance under conditions in which the pumps were not designed to operate. This information is specific to the pumps installed in a particular plant and is not currently available to the U.S. Nuclear Regulatory Commission (NRC) and its contractors. Consequently, no credit is given in this work for sustained pump operation after the NPSH margin decreases to zero.

The PRA model also recognizes the possibility that plant-operating personnel may take actions to restore the function of recirculation cooling by aligning other sources of water or to safely terminate the event by other means. This possibility is acknowledged by including an event titled “Recover from Loss of ECCS Recirc due to Debris” in the event trees. Although certain classes of recovery actions are generic, the ability to recover is highly plant-specific. Therefore, no attempt was made to quantitatively credit recovery actions, although possible recovery actions are discussed qualitatively in this report.

The event-tree models developed in this study acknowledge differences in the accident mitigation systems associated with the three major types of PWR containment designs (large dry, ice condenser, and subatmospheric) and also recognize some unique characteristics of recirculation cooling for Combustion Engineering (CE) plants. These are described in Sec. 3.0.

1.3 Data Used to Quantify the PRA Model

The primary sources of information used to support quantification of the baseline CDF model include the following.

- Previous NRC-sponsored PRA-related studies
- Individual Plant Examinations (IPEs)
- Updated Final Safety Analysis Reports (UFSARs)
- Publicly available vendor accident analyses
- Previous Los Alamos National Laboratory (LANL) risk studies

Data collected from these sources included values for parameters such as initiating-event frequencies, mitigating system (functional) failure probabilities, and other parameters included in the baseline event trees.

For the LOCAs, the event-tree accident sequences were quantified with two sets of initiating-event frequencies: the “traditional PRA” set and “the leak before break” set. The “traditional PRA” set of frequencies for LOCAs is the set used in most PRAs that have been performed and is basically the set of values used in the NUREG-1150 studies [2]. The “leak before break” frequencies for LOCAs are from NUREG/CR-5750 where credit for leak before break was included [3]. Attachment B to this report provides the specific frequencies for each of these two sets of frequencies. For the transients, one set of initiating-event frequencies was used: the “traditional PRA” set.

A large quantity of additional information was collected to support quantification of plant-specific values for loss of NPSH margin. These data are described in the companion report to this assessment [1], and the method used to translate the deterministic analysis of recirculation sump performance to failure probabilities is described in Sec. 4.0.

1.4 Contents of this Report

The remainder of this report provides further details of the accident types included in the analysis (Sec. 2.0), the event trees used to perform the CDF analysis (Sec. 3.0), the manner in which recirculation sump failure probabilities were derived (Sec. 4.0), and the results of the CDF analysis (Sec. 5.0). Conclusions from this study are given in Sec. 6.0.

To help explain this analysis, supporting information is provided in five appendices. Appendix A contains each of the event trees used to estimate CDF. Appendix B provides details on the quantification of the event-tree initiating events and mitigating system failures, along with major assumptions used to develop the event trees. Appendix B also describes important factors that affect sump availability. Appendix C tabulates the values of conditional failure probabilities used to characterize the loss of NPSH margin as a result of debris for ECCS recirculation using the sump. Estimates are provided for each of the 69 cases described in the parametric evaluations report and adapted to each of the accident sequences addressed in the current assessment. Appendix D provides a spreadsheet that summarizes the quantification of each of the core-damage sequences. Appendix E is an earlier letter report that provides background information on the accidents selected for analysis and on the overall approach for quantification of risk considering the effects of debris.

2.0 TYPES OF ACCIDENT ADDRESSED IN THE ANALYSIS

Recirculation sump degradation is a concern only in those accidents where pump suction must be aligned to the sump to provide long-term core and/or containment cooling. Thus, only a subset of the full spectrum of possible PWR accidents is applicable to this study. Various types of LOCAs may require ECCS sump availability for successful mitigation, for example, a design-basis large LOCA (LLOCA. Certain types of transients may also require ECCS sump availability for successful core cooling. For example, mitigation of a nonrecoverable loss-of-all-secondary-cooling condition would be possible only if primary system "feed and bleed" cooling can be established. The "feed-and-bleed" technique involves passing coolant out of the primary system through primary system relief valves (or safety valves at some plants) while simultaneously feeding the primary system with high-pressure injection system flow. Initially, coolant used for this high-pressure injection system flow is obtained from the refueling water storage tank (RWST) but once the tank empties continued use of "feed and bleed" requires switchover to sump recirculation cooling and subsequent sump availability.

With these facts, the accidents to be examined in this study were selected based on information from the following prior studies.

- An April 30, 1999, letter report to the NRC proposing accidents for specific analysis [4]
- The information provided in Appendix E to this report
- The recent LANL study of the debris phenomena in PWRs [1]

To facilitate a quantitative evaluation of the effect of debris-induced recirculation failure on CDF, the accidents of interest were grouped into the following general categories.

- Small Loss-of-Coolant Accident (SLOCA)
- Medium Loss-of-Coolant Accident (MLOCA)
- Large Loss-of-Coolant Accident (LLOCA)
- Transient with Stuck-Open Power-Operated Relief Valve (TRAN-PORV)
- Transient with Loss of All Feedwater, Main and Auxiliary (TRAN-LOFW)

In some cases, these categories were subdivided further to properly account for the specific mitigation systems required to successful prevent core damage (i.e., accident success criteria). These are described below.

The SLOCA category was subdivided into three subcategories [5]. The first (SLOCA-1) is a small LOCA with a break of equivalent diameter of less than about 1 in. Normal makeup can mitigate this size of break. This break category was not analyzed further.

The second SLOCA category (SLOCA-2) has a break size of equivalent diameter of between about 1 and 2 in.* High-head emergency coolant injection is required for this size break. The break size is sufficiently small such that energy out the break cannot match decay heat, and heat removal from either a steam generator or feed and bleed is required. If heat removal with a steam generator is available, it may be possible to depressurize the primary and use residual heat removal (RHR) in the shutdown cooling (SDC) mode before the ECCS switches from injection to recirculation.

The third SLOCA category (SLOCA-3) has a break size of equivalent diameter of between about 2 and 4 in. High-head emergency coolant injection is required for this size break. The break size is sufficiently large such that energy out the break can match decay heat. If heat removal with a steam generator is available, it may be possible to depressurize the primary and use RHR in the SDC mode before the ECCS switches from injection to recirculation. If heat removal with a steam generator is not available, it is assumed that it is not possible to depressurize and use RHR/SDC before switchover of ECCS from injection to recirculation.

The MLOCA has a break size of equivalent diameter of between about 4 to 6 in. Based on the Westinghouse four-loop plant used as the baseline for the model, this break is assumed to behave exactly as the SLOCA-3 in terms of

* Sometimes LOCAs in this size range are referred to as "very-small" LOCAs.

ECCS requirements with an additional requirement for accumulator injection. (For some plants, the MLOCA may have ECCS injection requirements more like those of a LLOCA than like those of a SLOCA-3.) Because of the size of the break, it is assumed that it is possible to depressurize and use RHR/SDC before switchover of the ECCS from injection to recirculation.

The LLOCA represents a break size diameter of about 6 in. or greater. This break size requires low-head ECCS core flow and accumulator injection.

The TRAN-PORV accident is functionally identical to the SLOCA-3 as a stuck-open power-operated relief valve (PORV) is equivalent to a LOCA break of about 2 in. in size. However, this accident was treated separately because its debris effects and recovery potential may be more favorable than for the SLOCA-3. Specifically, for the stuck-open PORV, the discharge is initially to the pressurizer quench tank, and release from that tank into containment only occurs after the pressure of the rupture disk on the quench tank is reached. This feature of the TRAN-PORV accident sequence is considered in the conditional probability for sump failure (Sec. 4.) Also, a possible action to recover from loss of ECCS recirculation is to depressurize and use RHR/SDC, and for this accident, the break is sufficiently high in elevation that it does not require continued makeup while on RHR/SDC. In contrast, the SLOCA-3 break may be in a location where continued makeup is required while on RHR/SDC.

The TRAN-LOFW involves the unavailability of both main and auxiliary feedwater. The only remaining option for core cooling is feed and bleed. Functionally, this accident is almost identical to the SLOCA-3 accident as feed and bleed requires use of a PORV that has a size equivalent to a LOCA break of about 2 in.

3.0 EVENT-TREE MODELS

This subsection describes the event-tree models used in the analysis. Included are descriptions of each sequence and the major assumptions used in the analysis.

The individual sequences specify the plant conditions that affect the likelihood that debris will cause loss of NPSH margin. That is, for a given sequence, there is a given set of system successes and failures that affect: the release of fluid to containment, the state of containment spray systems, the state of ECCS systems during injection and recirculation, the timing of switchover of ECCS from injection to recirculation, and the number of pumps pulling from the ECCS sump in recirculation. These system conditions are important in assessing the generation and transport of debris, and the effect of debris on loss of NPSH margin. Thus, a sequence-specific analysis is required to accurately quantify the CDF resulting from debris. The overall CDF for a given accident-initiating event is the statistical sum of all the constituent sequences.

One set of initiating events that has not been addressed to date is “external events,” for example, a seismic event. These events have two additional complications that the so-called “internal events” that have been addressed do not have. First, an external event affects many systems, structures, and components (SSCs) at the plant simultaneously; for example, a seismic event stresses all the SSCs at the plant. Second, an external event has a variable magnitude that determines its severity; for example, a seismic event has a range of ground accelerations and the likelihood of the magnitude of the ground acceleration is quantified as a frequency of exceedance curve. It is recognized that external events should be addressed, but as with recovery actions, a plant-specific analysis is needed for accurate quantification. Also, the seismic event itself could affect the debris phenomenology (generation and transport), and that dependency has not been considered for inclusion in the generic analyses.

3.1 Large LOCA Event Trees

Successful mitigation of a LLOCA was assumed to require two accumulators, one of two low-head safety injection (LHSI) trains, and one of two low-head safety recirculation (LHSR) trains. (Reactor trip is not required for a LLOCA as the vessel empties and ECCS injection uses borated water.) For plants having a subatmospheric containment, the core cooling systems do not have heat exchangers and must instead rely on cooling provided by the containment spray recirculation heat exchangers. For these plants, it was assumed that one containment spray recirculation heat exchanger would be needed to support core-cooling recirculation. (Other non-subatmospheric designs, such as CE designs, also may require containment spray for heat removal because in recirculation, high-head ECCS pumps are used in lieu of low-head ECCS pumps and heat exchangers are not part of the high-head recirculation system design at these plants.)

A general simplifying assumption made in all the event trees is that failure of containment spray injection automatically results in failure of containment spray recirculation. This assumption is based on the fact that the containment spray injection and recirculation systems typically share many common components, so that a failure that disables containment spray injection is likely to also disable containment spray recirculation.

The functional event trees referred to in this discussion were produced with the SAPHIRE software and are included in Attachment A [6]. The event trees are structured so that the progression of the accident is generally represented in a time-ordered manner from left to right. An upward branch underneath a given heading indicates that the function represented by that heading was successful. Conversely, a downward branch underneath a heading indicates that that function has failed.

3.1.1 Baseline LLOCA Sequences (No debris effects)

The baseline case LLOCA event tree does not include debris-related effects. The first event-tree heading (LLOCA) represents the initiating event (in this case a LLOCA), and the remaining headings represent various mitigating functions.

The quantification of each branch point ("split fraction") is described later.

Heading "ECCS-INJ-L," which immediately follows the initiating event, characterizes the success or failure of the ECCS injection function. The next heading (SPRAY-INJ) denotes the success or failure of the containment spray injection function. The remaining headings refer to success or failure of the following functions: ECCS recirculation (ECCS-RECIRC-L) and containment spray recirculation (SPRAY-RECIRC). The LLOCA baseline event tree contains a total of six sequences. Each of these sequences is characterized by a specific outcome as listed in the "END-STATE-NAMES" column at the far right of the page. The sequences are numbered individually.

In Sequence 1, the ECCS injection, containment spray injection, ECCS recirculation, and containment spray recirculation functions are all successful. As a result, the core cooling is successful as indicated by the "OK" in the "END-STATE-NAMES" column.

In Sequence 2, the ECCS injection, containment spray injection, and ECCS recirculation functions are successful, but containment spray recirculation fails. For plants having a subatmospheric containment (and possibly other designs, such as CE plants), heat removal is not included in the ECCS recirculation system lineup so failure of containment spray results in loss of all heat removal during recirculation with the result that core cooling fails during the recirculation mode.

In other plant designs where heat removal is provided by heat exchangers in the ECCS recirculation system, loss of containment spray does not fail core cooling.[5] Thus, for this sequence, the "END-STATE-NAMES" column denotes two separate outcomes: core damage ("CD") for the subatmospheric designs, and "OK" for the other plant designs where the core cooling systems have their own dedicated heat exchangers.

Sequence 3 involves successful ECCS and containment spray injection but subsequent failure of ECCS recirculation. Core damage occurs as a result.

In Sequence 4, success of ECCS injection and failure of containment spray injection are followed by successful ECCS recirculation. As discussed previously, containment spray recirculation is also assumed to have failed given failure of containment spray injection. For plants having a subatmospheric containment (and possibly other designs, such as CE plants), failure of containment spray results in loss of heat removal with the result that core cooling fails during the recirculation mode. In other plant designs where the core cooling systems have their own dedicated heat exchangers, loss of containment spray recirculation does not cause loss of heat removal. Thus, this sequence has two separate outcomes, core damage ("CD") for the subatmospheric designs, and "OK" for the other plant designs where the core cooling systems have their own dedicated heat exchangers.

Sequence 5 involves successful ECCS injection combined with failure of containment spray injection and failure of ECCS recirculation. Core damage occurs as a result.

In Sequence 6, ECCS injection fails, resulting in core damage.

3.1.2 LLOCA Sequences with Debris Effects

As discussed in Sec. 1 of this report, the model for debris includes three additional events beyond those included in the baseline event tree: (a) “Avoid Loss ECCS Recirc NPSH Margin due to Debris”, (b) “ECCS Recirc with Loss NPSH Margin,” and (c) “Recover from Loss of ECCS Recirc due to Debris.” These additional events were described in Sec. 1 of this report. As discussed in Sec. 1, the last two events in the tree address, respectively, the possibility that the pumps pulling from the sump continue to operate with loss of NPSH margin or

5 Credit was taken throughout the analysis for best-estimate containment failure pressure (~3 times design pressure), which implies that containment spray is not required to prevent containment overpressure. Equipment qualification concerns from loss of containment spray were not addressed as they are not addressed in most PRA models. Also, failure of containment isolation was not modeled with regard to its effect on core cooling because (a) it is a small contributor to core damage frequency and (b) it is not considered in the front-end portion of most PRA models.

that recovery actions can be performed to restore core cooling. These two events are highly pump-design- and plant-specific, respectively, and no attempt to quantify them was made in this study.

These events can be initiating-event-specific; for the LLOCA initiating event, the initiating-event-specific names as indicated in the event tree are (a) “DEBRIS_OK_L,” (b) “RECIRC_NPSHM_L,” and (c) “REC_DEBRIS_L,” where the “L” indicates a LLOCA.

Because debris-related effects are addressed explicitly with separate headings as described above, the functional headings for ECCS recirculation (ECCS-RECIRC-L) and containment spray recirculation (SPRAY-RECIRC) do not include the effects of debris; they are exactly the same events as in the baseline event tree with no consideration of debris. The addition of debris-related headings results in nine LLOCA sequences.

In Sequence 1, ECCS injection, containment spray injection, ECCS recirculation (exclusive of debris considerations), and containment spray recirculation (exclusive of debris considerations) are successful. In addition, debris effects are benign, as sufficient NPSH margin is maintained for the ECCS recirculation pumps (indicated by the upward branch underneath “DEBRIS-OK-L”). As a result, the core cooling is successful.

In Sequence 2, ECCS injection, containment spray injection, ECCS recirculation (exclusive of debris considerations), and containment spray recirculation (exclusive of debris considerations) are successful. However, debris effects are severe enough so that the ECCS recirculation pumps have insufficient NPSH margin. Assuming no credit for pump operation with insufficient NPSH margin or recovery actions, core damage results.

In Sequence 3, the ECCS injection, containment spray injection, and ECCS recirculation functions are successful, but containment spray recirculation fails (for reasons other than debris). Debris-related effects are benign as sufficient NPSH margin is maintained for the ECCS recirculation pumps. For plants having a subatmospheric containment (and possibly other designs, such as CE plants), the failure of containment spray (non-debris-related) results in loss of heat removal with the result that core cooling fails during the recirculation mode. For the other plant designs, core cooling is maintained successfully.

Sequence 4 is similar to Sequence 3 except that debris effects are severe enough so that the ECCS recirculation pumps have insufficient NPSH margin. Core damage occurs as a result.

Sequence 5 involves successful ECCS injection combined with failure of containment spray injection and failure of ECCS recirculation (for reasons other than debris). Core damage occurs as a result.

In Sequence 6, success of ECCS injection and failure of containment spray injection is followed by successful ECCS recirculation (exclusive of debris effects). Debris-related effects are benign as sufficient NPSH margin is maintained for the ECCS recirculation pumps. For plants having a subatmospheric containment (and possibly other designs, such as CE plants), the failure of containment spray (non-debris-related) results in loss of heat removal with the result that core cooling fails during the recirculation mode. For the other plant designs, core cooling is maintained successfully. Thus, this sequence has two separate outcomes: core damage ("CD") for the subatmospheric designs and "OK" for the other plant designs where the core cooling systems have their own dedicated heat exchangers.

Sequence 7 is similar to Sequence 6, except that debris effects are severe enough that the ECCS recirculation pumps have insufficient NPSH margin. Core damage occurs as a result.

Sequence 8 involves successful ECCS injection combined with failure of containment spray injection and failure of ECCS recirculation (for reasons other than debris). Core damage occurs as a result.

In Sequence 9, ECCS injection fails, resulting in core damage.

3.1.3 LLOCA Mitigation

For those sequences involving loss of NPSH margin because of debris, it is possible that the ECCS pumps could continue to operate with loss of NPSH margin; a pump-specific analysis is required to quantify this likelihood.

There are two possible plant-specific strategies to recover from loss of the ECCS sump because of debris during a LLOCA.

1. Continue injection.
2. Restore the ability to recirculate from the sump

To continue injection, a source of borated water must be found and lined up for use, and concerns with overfilling the containment with water must be addressed. Also, the complexity of reswitching the ECCS from recirculation back to injection should be evaluated.

To restore the ability to recirculate from the sump, it may be possible to restore NPSH margin by decreasing the flow through the sump. Spray pumps and one train of ECCS pumps could be turned off or throttled (if possible). For plants in which sprays provide heat removal, turning off all spray trains would not be acceptable. It may be possible to use high-head ECCS pumps (which have a lower flow) for recirculation instead of low-head pumps if the pump design allows extended operation at low pressure without runout; also, heat removal using a spray train or possibly fan coolers must be provided as there is typically no heat removal in the ECCS systems without using the low-head ECCS pumps. (At some plants, the fan coolers, if present in the plant, are tripped on initiation of ECCS. At some plants the spray system has no heat removal capability as it does not incorporate heat exchangers.)

For subatmospheric plants, operators might receive an early indication of debris-induced pump flow problems because the inside and outside spray recirculation pumps are designed to start drawing coolant from the sump within 2 and 5 min, respectively, after ECCS actuation, whereas the other ECCS pumps (LPSI, HPSI, and containment spray injection) initially draw suction from the RWST. Abnormal operation of the recirculation pumps before spray recirculation switchover of the remaining ECCS pumps might provide the operators with an opportunity to minimize sump flow by securing redundant ECCS pump trains, thereby increasing the likelihood that core cooling will be maintained.

3.2 Medium LOCA Event Trees

Successful mitigation of a MLOCA was assumed to require reactor trip, one accumulator, one of two high-head safety injection (HHSI) trains, and one of two high-head safety recirculation (HHSR) trains piggybacked on one of two LHSR trains. For plants having a subatmospheric containment, the core cooling systems do not have heat exchangers and must instead rely on cooling provided by the containment spray recirculation heat exchangers. For these plants, it was assumed that one containment spray recirculation heat exchanger would be needed to support core-cooling recirculation. (Other non-subatmospheric designs, such as CE designs, also may require containment spray for heat removal because in recirculation, high-head ECCS pumps are used in lieu of low-head ECCS pumps, and heat exchangers are not part of the high-head recirculation system design at these plants.)

The baseline case MLOCA event tree does not include debris-related effects. The first event-tree heading (MLOCA) represents the initiating event (in this case, a MLOCA). Success or failure of reactor trip is not included in the event tree as failure of reactor trip is not a dominant contributor for this initiating event.

Heading "ECCS-INJ-M," which immediately follows the initiating event, characterizes the success or failure of the ECCS injection function. The next heading (SPRAY-INJ) denotes the success or failure of the containment spray function. The remaining headings refer to success or failure of the following functions: ECCS recirculation (ECCS-RECIRC-M) and containment spray recirculation (SPRAY-RECIRC). (The prefix or suffix “M” used on some of these events is used to specifically distinguish the MLOCA from other accidents with regard to event quantification. In the LLOCA event tree, the prefix or suffix “L” was used on these types of events.)

The MLOCA event tree with consideration of debris includes the three additional function-level headings beyond those included in the baseline event tree as discussed in Sec. 1. These headings are similar to those added to the LLOCA event tree. (Again, the suffix “M” is used on these events to specifically denote the MLOCA from other accidents). The first of these headings, "DEBRIS-OK-M," characterizes the ECCS pump NPSH margin. The next heading, "RECIRC-NPSHM-M," represents the possibility that ECCS pumps would continue to operate even with loss of adequate NPSH margin. The remaining of these three headings, "REC-DEBRIS-M," represents the possibility that debris-related recirculation loss could be recovered. Again, the branches underneath the "RECIRC-NPSHM-M" and "REC-DEBRIS-M" were not developed because the potential success of these events is highly pump-design- and plant-specific, and thus, it is not feasible to develop accurate generic estimates for the likelihood of success/failure of these events.

The MLOCA event trees have an sequence structure identical to the corresponding LLOCA event trees, i.e., the descriptions of the MLOCA sequences are identical to the LLOCA sequences from a functional standpoint. Thus, the MLOCA sequences will not be described further. (It is noted that the specific systems supporting the event-tree functions differ between the LLOCA and the MLOCA; for example, for the LLOCA, ECCS injection requires low-head ECCS pumps, whereas for the plant used as the basis for this study, a MLOCA required high-head ECCS injection.)

For those sequences involving loss of NPSH margin because of debris, it is possible that the ECCS pumps could continue to operate with loss of NPSH margin; a pump-specific analysis is required to quantify this likelihood.

There are three possible plant-specific strategies to recover from loss of the ECCS sump because of debris during a MLOCA.

1. Continue injection, or
2. Use SDC with makeup, or
3. Restore the ability to recirculate from the sump.

To continue injection, a source of borated water must be found and lined-up for use, and concerns with overfilling the containment with water must be addressed. Also, the complexity of reswitching the ECCS from recirculation back to injection should be evaluated.

In the model, the MLOCA is of sufficient size such that the primary system depressurizes to where the shutdown cooling system could be used for heat removal. However, makeup of borated water for loss out the break is required as well.

To restore the ability to recirculate from the sump, it may be possible to restore NPSH margin by decreasing the flow through the sump. Spray pumps and one train of ECCS pumps could be turned off or throttled (if possible). Turning off all spray trains would not be acceptable for plants in which sprays provide heat removal.

For MLOCAs, another possible strategy would be to turn off train(s) of containment spray during the injection mode of the accident, which would reduce the amount of debris transported to the sump, thereby reducing the likelihood of loss of NPSH margin.

3.3 Small LOCA Event Trees

3.3.1 SLOCA-3 Event Trees

Successful mitigation of a Sze 3 SLOCA was assumed to require reactor trip, one of two HHSI trains, and one of two HHSR trains piggybacked on one of two LHSR trains. For plants having a subatmospheric containment, the core cooling systems do not have heat exchangers and must instead rely on cooling provided by the containment spray recirculation heat exchangers. For these plants, it was assumed that one containment spray recirculation heat exchanger would be needed to support core-cooling recirculation. (Other non-subatmospheric designs, such as CE designs, also may require containment spray for heat removal because in recirculation, high-head ECCS pumps are used in lieu of low-head ECCS pumps, and heat exchangers are not part of the high-head recirculation system design at these plants.)

The baseline event tree for the Size 3 SLOCA does not include debris-related effects. The first event-tree heading (SLOCA3) represents the initiating event (in this case, a SLOCA with an equivalent size range of a 2- to 4-in. pipe break). Success or failure of reactor trip is not included in the event tree as failure of reactor trip is not a dominant contributor for this initiating event.

Heading "ECCS-INJ-S3," which immediately follows the initiating event, characterizes the success or failure of the ECCS high-pressure injection function. The next heading (SPRAY-INJ) denotes the success or failure of the containment spray injection function. The remaining headings refer to success or failure of the following functions: ECCS recirculation (ECCS-RECIRC-S3) and containment spray recirculation (SPRAY-RECIRC). (The use of prefix/suffix codes “S” and “S3” on some of these events specifically distinguishes the SLOCA-3 from other accidents with regard to event quantification).

The debris version of the SLOCA-3 event tree includes three additional function-level headings beyond those included in the baseline event tree: "DEBRIS-OK-S3" characterizes the ECCS pump NPSH margin. The next heading, "RECIRC-NPSHMS3” represents the possibility that ECCS pumps would continue to operate even with loss of adequate NPSH margin. The remaining of these three headings, "REC-DEBRIS-S3," represents the possibility that debris-related recirculation loss could be recovered. Again, the branches underneath the "RECIRC-NPSHMS3" and "REC-DEBRIS-S3" were not developed because potential success of these events is highly pump-design- and plant-specific, and thus, it is not feasible to develop generic estimates for the likelihood of success/failure.

The SLOCA-3 event trees have a sequence structure identical to the corresponding MLOCA and LLOCA event trees, i.e., the descriptions of the SLOCA-3 sequences are identical to the medium and LLOCA sequences from a functional standpoint. Thus, the SLOCA-3 sequences will not be described further.

For those sequences involving loss of NPSH margin because of debris, it is possible that the ECCS pumps could continue to operate with loss of NPSH margin; a pump-specific analysis is required to quantify this likelihood.

There are three possible plant-specific strategies to recover from loss of the ECCS sump because of debris during a Size 3 SLOCA.

1. Continue injection, or
2. Depressurize and use SDC with makeup, or
3. Restore the ability to recirculate from the sump

To continue injection, a source of borated water must be found and lined-up for use, and concerns with overfilling the containment with water must be addressed. The complexity of reswitching ECCS from recirculation back to injection also should be evaluated.

In the model, the Size 3 SLOCA is of such a size that cooling with a steam generator is required to depressurize in a timely manner to where the shutdown cooling system could be used for heat removal. Makeup of borated water for loss out the break is required as well.

To restore the ability to recirculate from the sump, it may be possible to restore the NPSH margin by decreasing the flow through the sump. Spray pumps and one train of ECCS pumps could be turned off or throttled (if possible). For plants in which sprays provide heat removal, turning off all spray trains would not be acceptable.

For SLOCAs another possible strategy would be to turn off train(s) of containment spray during the injection mode of the accident, which would reduce the amount of debris transported to the sump, thereby reducing the likelihood of loss of NPSH margin.

3.3.2 SLOCA-2 Event Trees

Successful mitigation of a Size 2 SLOCA was assumed to require reactor trip, one of two HHSI trains, one of two HHSR trains piggybacked on one of two LHSR trains, and heat removal using either one steam generator or feed and bleed through one pressurizer relief valve. For plants having a subatmospheric containment, the core cooling systems do not have heat exchangers and must instead rely on cooling provided by the containment spray recirculation heat exchangers. For these plants, it was assumed that one containment spray recirculation heat exchanger would be needed to support core-cooling recirculation unless cooling with a steam generator is provided. (Other non-subatmospheric designs, such as CE designs, also may require containment spray for heat removal because in recirculation, high-head ECCS pumps are used in lieu of low-head ECCS pumps, and heat exchangers are not part of the high-head recirculation system design at these plants.)

The SLOCA-2 initiator represents a break size of diameter between about 1 and 2 in. For this size break, high-head emergency coolant injection is required. The break size is sufficiently small such that energy out the break cannot match decay heat and heat removal from either a steam generator, or feed and bleed is required. If heat removal with a steam generator is available, it may be possible to depressurize the primary and use RHR in the SDC mode before the ECCS switches from injection to recirculation. If steam generator cooling is not available and feed and bleed is used instead for core cooling, it is assumed not possible to depressurize and use RHR/SDC before switchover of the ECCS from injection to recirculation.

For large dry containment designs having fan coolers that remain operational after an ECCS actuation signal and for which the actuation set point for spray injection is sufficiently high, it is assumed that operation of the fan coolers will prevent automatic actuation of the containment sprays. The fan coolers are included in the model because if fan coolers can prevent actuation of containment spray, the amount of debris transported to the sump can be reduced significantly.

The baseline event tree for the Size 2 SLOCA does not include debris-related effects. The first event-tree heading (SLOCA2) represents the initiating event (in this case, a SLOCA with a equivalent size range of a 1- to 2-in. pipe break). Success or failure of reactor trip is not included in the event tree as failure of reactor trip is not a dominant contributor for this initiating event.

Heading "ECCS-INJ-S2," which immediately follows the initiating event, characterizes the success or failure of ECCS injection function. The third heading (“SG”) represents heat removal with the steam generators. The fourth heading (“FB”) represents operator actions to open a primary system PORV to support feed and bleed cooling. The fifth heading (“FAN-COOL”) refers to availability of the fan coolers for preventing automatic actuation of containment spray injection. The sixth heading (“SPRAY-INJ”) denotes the success or failure of the containment spray function. The remaining headings refer to ECCS recirculation (“ECCS-RECIRC-S2”) and containment spray (“SPRAY-RECIRC”).

3.3.2.1 Baseline SLOCA-2 Sequences (No Debris Effects)

The SLOCA-2 baseline event tree contains a total of 14 sequences. The upward branch underneath the “FAN-COOL” heading is potentially applicable only to large dry containment plants that have a high-pressure spray actuation set point and fan coolers operational following an ECCS actuation signal. Consequently, Sequences 1 and 2 are only applicable to these types of large dry plants.

Sequences 1 through 7 involve successful use of secondary system (steam generator) cooling for the additional required amount of heat removal to match decay heat (the energy out the break cannot match the decay heat.) In Sequence 1, adequate core cooling is achieved through the success of ECCS injection, steam generator cooling, and ECCS recirculation. The fan coolers successfully prevent automatic actuation of containment spray injection (large dry containments with a high spray actuation set point only), though in this sequence this action does not influence the success of core cooling.

In Sequence 2, adequate core cooling initially is achieved through the success of ECCS injection and steam generator cooling. However, subsequent loss of ECCS recirculation (for reasons other than debris) leads to core damage. Although it does not prevent core damage from occurring, the fan coolers do prevent automatic containment spray actuation.

In Sequence 3, the ECCS injection, steam generator cooling, containment spray injection, ECCS recirculation, and containment spray recirculation functions are all successful. As a result, core cooling is successful. This sequence also involves the inability of fan coolers (or lack of fan coolers) to prevent automatic actuation of containment spray injection.

Sequence 4 is similar to Sequence 3, except that containment spray recirculation fails. Because heat removal with a steam generator is provided, there is no core damage even for plants with no heat removal capability in the ECCS recirculation lineup.

In Sequence 5, ECCS injection, steam generator cooling, and containment spray injection are all successful. However, because ECCS recirculation subsequently fails (for reasons other than debris), core damage occurs. This sequence also involves the inability of fan coolers (or lack of fan coolers) to prevent automatic actuation of containment spray injection.

In Sequence 6, ECCS injection, steam generator cooling, and ECCS recirculation are successful. However, containment spray injection fails, and as a consequence, containment recirculation also fails (Assumption 7). Because heat removal with a steam generator is provided, there is no core damage even for plants with no heat removal capability in the ECCS recirculation lineup. This sequence also involves the inability of fan coolers (or a lack of fan coolers) to prevent automatic actuation of containment spray injection.

In Sequence 7, ECCS injection and steam generator cooling are successful. However, ECCS recirculation fails (for causes other than debris), thereby resulting in core damage. Containment spray injection also fails and as a consequence, containment recirculation also fails (Assumption 7). However, these containment spray failures do not influence the sequence outcome. This sequence also involves the inability of fan coolers (or a lack of fan coolers) to prevent automatic actuation of containment spray injection, although again this action does not influence the sequence outcome.

Sequences 8 through 13 involve the failure of steam generator cooling. Feed and bleed cooling is credited as an alternate means to steam generator cooling for the additional required amount of heat removal to match decay heat (the energy out the break cannot match the decay heat.) It is assumed that use of feed and bleed discharges sufficient energy to the containment such that spray action will occur even with operation of fan coolers (Assumption 13).

In Sequence 8, ECCS injection, feed and bleed cooling, containment spray injection, ECCS recirculation, and containment spray recirculation are all successful. As a result, core cooling is successful.

Sequence 9 is similar to Sequence 8, except that containment spray recirculation fails. For plants having a subatmospheric containment (and possibly other designs, such as CE plants), failure of containment spray results in loss of heat removal with the result that core cooling fails during the recirculation mode. In other plant designs where the core cooling systems have their own dedicated heat exchangers, loss of containment spray recirculation does not fail core cooling. Thus, core damage occurs for the subatmospheric designs, whereas core damage is avoided for the other plant designs.

In Sequence 10, ECCS injection, feed and bleed cooling, and containment spray injection are successful. However, because ECCS recirculation subsequently fails (for reasons other than debris), core damage occurs.

In Sequence 11, ECCS injection, feed and bleed cooling and ECCS recirculation are successful. However, containment spray injection fails and, as a consequence, containment recirculation also fails (Assumption 7). For plants having a subatmospheric containment (and possibly other designs, such as CE plants), failure of containment spray results in loss of heat removal with the result that core cooling fails during the recirculation mode. In other plant designs where the core cooling systems have their own dedicated heat exchangers, loss of containment spray recirculation does not fail core cooling. Thus, core damage occurs for the subatmospheric designs, whereas core damage is avoided for the other plant designs.

In Sequence 12, ECCS injection and feed and bleed cooling are successful. However, ECCS recirculation fails (for reasons other than debris), resulting in core damage. Containment spray injection also fails and, as a consequence, containment spray recirculation also fails (Assumption 7). However, these containment spray failures do not influence the sequence outcome.

Sequence 13 involves successful ECCS injection. However, both steam generator cooling and feed and bleed cooling fail. As a result, core damage occurs.

In Sequence 14, ECCS injection fails resulting in core damage.

3.3.2.2 SLOCA-2 Sequences with Debris

The debris version of the SLOCA-2 event tree includes three additional function-level headings beyond those included in the baseline event tree: "DEBRIS-OK-S2" characterizes the ECCS pump NPSH margin. The next heading, "RECIRC-NPSHMS2," represents the possibility that the ECCS pumps would continue to operate even with loss of adequate NPSH margin. The remaining of these three headings, "REC-

DEBRIS-S2," represents the possibility that debris-related recirculation loss could be recovered. Again, the branches underneath the "RECIRC-NPSHMS2" and "REC-DEBRIS-S2" were not developed because the potential success of these events is highly plant-specific, and thus, it is not feasible to develop generic estimates for the likelihood of success/failure.

Because debris-related effects are addressed explicitly with separate headings as described above, the functional headings for ECCS recirculation (ECCS-RECIRC-S2) and containment spray recirculation (SPRAY-RECIRC) do not include these effects.

In Sequence 1, ECCS injection, steam generator cooling, and ECCS recirculation (exclusive of debris considerations) are successful. In addition, debris effects are benign as sufficient NPSH margin is maintained for the ECCS recirculation pumps (indicated by the upward branch underneath “DEBRIS-OK-S2”). As a result, core cooling is successful. The fan coolers successfully prevent automatic actuation of containment spray injection (large dry containments with a high spray actuation set point only), although in this sequence, this action does not influence the success of core cooling.

In Sequence 2, ECCS injection, steam generator cooling, and ECCS recirculation (exclusive of debris considerations) are successful. However, debris effects are severe enough that the ECCS recirculation pumps have insufficient NPSH margin. When no credit for recovery actions or pump operation with insufficient NPSH margin is assumed, core damage results. The fan coolers successfully prevent automatic actuation of containment spray injection (large dry containments only), although in this sequence this action does not influence the sequence results.

In Sequence 3, adequate core cooling initially is achieved through the success of ECCS injection and steam generator cooling. However, subsequent loss of ECCS recirculation (for reasons other than debris) leads to core damage. Although it does not prevent core damage from occurring, the fan coolers do prevent automatic containment spray actuation.

In Sequence 4, the ECCS injection, steam generator cooling, containment spray injection, ECCS recirculation, and containment spray recirculation functions are all successful. In addition, debris effects are benign as sufficient NPSH margin is maintained for the ECCS recirculation pumps. As a result, core cooling is successful. This sequence also involves the inability of fan coolers (or a lack of fan coolers) to prevent automatic actuation of containment spray injection, although this action does not influence the sequence outcome.

Sequence 5 similar to Sequence 4 except that debris effects are severe enough that the ECCS recirculation pumps have insufficient NPSH margin. Assuming no credit for recovery actions or pump operation with insufficient NPSH margin, core damage results.

Sequence 6 is similar to Sequence 4, except that containment spray recirculation fails. Because heat removal with a steam generator is provided, there is no core damage even for plants with no heat removal capability in the ECCS recirculation lineup. (Here debris effects are benign as sufficient NPSH margin is maintained for the ECCS recirculation pumps).

Sequence 7 is similar to Sequence 6, except that debris effects are severe enough that the ECCS recirculation pumps have insufficient NPSH margin. Assuming no credit for recovery actions or pump operation with insufficient NPSH margin, core damage results.

In Sequence 8, ECCS injection, steam generator cooling, and containment spray injection are all successful. However, because ECCS recirculation subsequently fails (for reasons other than debris), core damage occurs. This sequence also involves the inability of fan coolers (or a lack of fan coolers) to prevent automatic actuation of containment spray injection, though this action does not influence the sequence outcome.

In Sequence 9, ECCS injection, steam generator cooling, and ECCS recirculation are successful, but containment spray injection and recirculation fail. Because heat removal with a steam generator is provided, there is no core damage even for plants with no heat removal capability in the ECCS recirculation lineup.

This sequence also involves the inability of fan coolers (or a lack of fan coolers) to prevent automatic actuation of containment spray injection, although this action does not influence the sequence outcome. (Here debris effects are benign as sufficient NPSH margin is maintained for the ECCS recirculation pumps).

Sequence 10 is similar to Sequence 9, except that debris effects are severe enough that the ECCS recirculation pumps have insufficient NPSH margin. Assuming no credit for recovery actions or pump operation with insufficient NPSH margin, core damage results.

In Sequence 11, ECCS injection and steam generator cooling are successful. However, ECCS recirculation fails (for reasons other than debris), thereby resulting in core damage. Containment spray injection also fails and, as a consequence, containment recirculation also fails (Assumption 7). However, these containment spray failures do not influence the sequence outcome. This sequence also involves the inability of fan coolers (or a lack of fan coolers) to prevent automatic actuation of containment spray injection, though again this action does not influence the sequence outcome.

In Sequence 12, steam generator cooling is lost, but feed and bleed is successful. ECCS injection, containment spray injection, ECCS recirculation, and containment spray recirculation are all successful as well. Also, debris effects are benign as sufficient NPSH margin is maintained for the ECCS recirculation pumps. As a result, core cooling is successful.

Sequence 13 is similar to Sequence 12, except that debris effects are severe enough that the ECCS recirculation pumps have insufficient NPSH margin. Assuming no credit for recovery actions or pump operation with insufficient NPSH margin, core damage results.

Sequence 14 is similar to Sequence 12, except that containment spray recirculation fails (for reasons other than debris). For plants having a subatmospheric containment (and possibly other designs, such as CE plants), failure of containment spray results in loss of heat removal with the result that core cooling fails during the recirculation mode. In other plant designs where the core cooling systems have their own dedicated heat exchangers, loss of containment spray recirculation does not fail core cooling. Thus, core damage occurs for the subatmospheric designs, whereas core damage is avoided for the other plant designs.

Sequence 15 is similar to Sequence 14, except that debris effects are severe enough that the ECCS recirculation pumps have insufficient NPSH margin. Assuming no credit for recovery actions or pump operation with insufficient NPSH margin, core damage results.

In Sequence 16, ECCS injection, feed and bleed cooling, and containment spray injection are successful. However, because ECCS recirculation subsequently fails (for reasons other than debris), core damage occurs.

In Sequence 17, ECCS injection, feed and bleed cooling, and ECCS recirculation are successful. Also, debris effects are benign as sufficient NPSH margin is maintained for the ECCS recirculation pumps. However, containment spray injection fails, and as a consequence, containment recirculation also fails (Assumption 7). For plants having a subatmospheric containment (and possibly other designs, such as CE plants), failure of containment spray results in loss of heat removal with the result that core cooling fails during the recirculation mode. In other plant designs where the core cooling systems have their own dedicated heat exchangers, loss of containment spray recirculation does not fail core cooling. Thus, core damage occurs for the subatmospheric designs, whereas core damage is avoided for the other plant designs.

Sequence 18 is similar to Sequence 17, except that debris effects are severe enough that the ECCS recirculation pumps have insufficient NPSH margin. Assuming no credit for recovery actions or pump operation with insufficient NPSH margin, core damage results.

In Sequence 19, ECCS injection and feed and bleed cooling are successful. However, ECCS recirculation fails (for reasons other than debris), thereby resulting in core damage. Containment spray injection also fails and, as a consequence, containment recirculation also fails (Assumption 7). However, these containment spray failures do not influence the sequence outcome.

Sequence 20 involves successful ECCS injection. However, both steam generator cooling and feed and bleed cooling fail (for reasons other than debris). As a result, core damage occurs.

In Sequence 21, ECCS injection fails resulting in core damage.

3.3.2.3 SLOCA-2 Mitigation

For those sequences involving loss of NPSH margin from debris, it is possible that the ECCS pumps could continue to operate with loss of NPSH margin; a pump-specific analysis is required to quantify this likelihood. There are three possible plant-specific strategies to recover from loss of the ECCS sump resulting from debris during a Size 2 SLOCA:

1. Continue injection, or
2. Depressurize and use SDC with makeup, or
3. Restore the ability to recirculate from the sump.

To continue injection, a source of borated water must be found and lined-up for use, and concerns with overfilling the containment with water must be addressed. Also, the complexity of reswitching the ECCS from recirculation back to injection should be evaluated.

In the model, the Size 2 SLOCA is of such a size that cooling with a steam generator is required to depressurize in a timely manner to where the shutdown cooling system could be used for heat removal. Makeup of borated water for loss out the break is required as well.

To restore the ability to recirculate from the sump, it may be possible to restore NPSH margin by decreasing the flow through the sump. Spray pumps and one train of ECCS pumps could be turned off or throttled (if possible). For plants in which sprays provide heat removal, turning off all spray trains would not be acceptable.

For SLOCAs, another possible strategy would be to turn off train(s) of containment spray during the injection mode of the accident, which would reduce the amount of debris transported to the sump, thereby reducing the likelihood of loss of NPSH margin. Use of fan coolers in lieu of containment spray is also another way to reduce the amount of debris transported to the sump; this may not be possible in plants that either isolate fan coolers on ECCS actuation or that have low a low set point for actuation of containment spray.

3.4 Transient with Stuck-Open PORV

The “Transient with Stuck-Open PORV” event trees have a sequence structure and success criteria identical to the corresponding SLOCA-3 event trees (i.e., the ECCS injection and recirculation headings are the same ones used for SLOCA-3, namely "ECCS-INJ-S3" and “ECCS-RECIRC-S3).”

The stuck-open PORV is a unique SLOCA. Discharge is into a pressurizer quench tank instead of directly to containment, which potentially reduces the amount of debris generated. It is possible to stop the leak by closing the block valve located upstream of the PORV. The leak is sufficiently elevated that if shutdown cooling is used, no makeup is required (except over the long term to compensate for losses through pipe fittings and shutdown pump seals.)

The baseline event tree for the stuck-open PORV does not include debris-related effects. The first event-tree heading (TRANS-OPEN-PORV) represents the initiating event (in this case a SLOCA with a equivalent size range of a 1- to 2-in. pipe break). Success or failure of reactor trip is not included in the event tree as failure of reactor trip is not a dominant contributor for this initiating event.

The debris version of the “Transient with Stuck Open PORV” event tree includes three additional function-level headings beyond those included in the baseline event tree: "DEBRIS-OK-PO" characterizes the ECCS pump NPSH margin. The next heading, "RECIRC-NPSHMPO," represents the possibility that ECCS pumps would continue to operate even with loss of adequate NPSH margin. The remaining of these three headings, "REC-DEBRIS-PO," represents the possibility that debris-related recirculation loss could be recovered. Again, the branches underneath the "RECIRC-NPSHMPO" and "REC-DEBRIS-PO" were not developed because the potential success of these events is highly plant-specific, and thus, it is not feasible to develop generic estimates for the likelihood of success/failure. Note that these three debris-related events are different than the corresponding SLOCA-3 events (“PO” instead of “S3” suffix) to allow for potentially more favorable debris effects and recovery potential.

Because the “Transient with Stuck Open PORV” event trees have an identical sequence structure to the corresponding SLOCA-3 event trees, the “Transient with Stuck Open PORV” sequences will not be described further.

For those sequences involving loss of NPSH margin because of debris, it is possible that the ECCS pumps could continue to operate with loss of NPSH margin; a pump-specific analysis is required to quantify this likelihood.

There are three possible plant-specific strategies to recover from loss of the ECCS sump due to debris during a stuck open relief valve.

1. Continue injection, or
2. Depressurize and use SDC, or
3. Restore the ability to recirculate from the sump

To continue injection, a source of borated water must be found and lined-up for use, and concerns with overfilling the containment with water must be addressed. The complexity of reswitching the ECCS from recirculation back to injection should be evaluated as well.

In the model, the stuck-open PORV is of such a size that cooling with a steam generator is required to depressurize in a timely manner to where the shutdown cooling system could be used for heat removal. Makeup of borated water for loss out the break is not required because of the high elevation of the PORV relative to the shutdown cooling drop line elevation. (Makeup is required over the long term to compensate for losses through pipe fittings and shutdown pump seals.)

To restore the ability to recirculate from the sump, it may be possible to restore NPSH margin by decreasing the flow through the sump. Spray pumps and one train of ECCS pumps could be turned off or throttled (if possible). For plants in which sprays provide heat removal, turning off all spray trains would not be acceptable.

For SLOCAs, another possible strategy would be to turn off train(s) of containment spray during the injection mode of the accident, which would reduce the amount of debris transported to the sump, thereby reducing the likelihood of loss of NPSH margin.

Also, for the stuck-open relief valve, another recovery option is to isolate the leak using the block valve located upstream of the PORV and provide heat removal using a steam generator.

3.5 Loss of Main and Auxiliary Feedwater

Functionally, the loss-of-feedwater (LOFW) event trees are very similar to the SLOCA-3 event trees as feed and bleed cooling uses a PORV that has a size equivalent to a LOCA break of about 2 in.

The baseline event tree for LOFW does not include debris-related effects. The first event-tree heading (LOFW) represents the initiating event, loss of main and auxiliary feedwater. Success or failure of reactor trip is not included in the event tree as failure of reactor trip is not a dominant contributor for this initiating event.

The second heading (“FB”) represents operator actions to open a primary system PORV to support feed and bleed cooling. The third heading "ECCS-INJ-S3" characterizes the success or failure of the ECCS injection function. This heading indicates that the same success criteria used for SLOCA-3 ECCS injection is also applicable to supporting feed and bleed function for LOFW.

The fourth heading (“FAN-COOL”) refers to availability of the fan coolers for preventing automatic actuation of containment spray injection. The fifth heading (SPRAY-INJ) denotes the success or failure of the containment spray function. The remaining headings refer to success or failure of ECCS recirculation (ECCS-RECIRC-S3) and containment spray (SPRAY-RECIRC). Note that the same success criteria used for SLOCA-3 ECCS recirculation (ECCS-RECIRC-S3) is also applicable to supporting the LOFW feed and bleed function.

The LOFW baseline event tree contains a total of seven sequences. The “FAN-COOL” heading is shown for completeness. This event is potentially applicable for discharges of coolant to containment only for large dry containment plants that have a high-pressure spray set point and fan coolers operational following an ECCS actuation signal. However, it is assumed that use of feed and bleed discharges sufficient energy to containment such that spray action will occur even with operation of fan coolers (Assumption 13). Thus, no branch points are reflected underneath the “FAN-COOL” heading.

3.5.1 Baseline LOFW Sequences (No debris effects)

In Sequence 1, feed and bleed (PORV opened), ECCS injection, containment spray injection, ECCS recirculation, and containment spray recirculation are all successful. As a result, the core cooling is successful.

In Sequence 2, feed and bleed (PORV opened), ECCS injection, containment spray injection, and ECCS recirculation are successful, but containment spray recirculation fails. For plants having a subatmospheric containment (and possibly other designs, such as CE plants), failure of containment spray results in loss of heat removal with the result that core cooling fails during the recirculation mode. In other plant designs where the core cooling systems have their own dedicated heat exchangers, loss of containment spray recirculation does not fail core cooling. Thus, for this sequence, core damage occurs for the subatmospheric designs, whereas core cooling is adequate for the other plant designs.

Sequence 3 involves successful feed and bleed (PORV opened), ECCS, and containment spray injection but subsequent failure of ECCS recirculation. Core damage occurs as a result.

In Sequence 4, success of feed and bleed (PORV opened), success of ECCS injection, and failure of containment spray injection are followed by successful ECCS recirculation. Per Assumption 7, containment spray recirculation also is assumed to have failed given failure of containment spray injection. For plants having a subatmospheric containment (and possibly other designs, such as CE plants), failure of containment spray results in loss of heat removal with the result that core cooling fails during the recirculation mode. In other plant designs where the core cooling systems have their own dedicated heat exchangers, loss of containment spray recirculation does not fail core cooling. Thus, core damage occurs for the subatmospheric designs, whereas core cooling is adequate for the other plant designs.

Sequence 5 involves successful feed and bleed and ECCS injection combined with failure of containment spray injection and failure of ECCS recirculation. Core damage occurs as a result.

In Sequence 6, ECCS injection fails, resulting in core damage.

Finally, in Sequence 7, operators are unsuccessful in opening a PORV to support feed and bleed cooling. This failure results in core damage.

3.5.2 LOFW Sequence with Debris Effects

The debris version of the LOFW event tree includes three additional function-level headings beyond those included in the baseline event tree: "DEBRIS-OK-LF," characterizes the ECCS pump NPSH margin. The next heading, "RECIRC-NPSHMLF," represents the possibility that ECCS pumps would continue to operate even with loss of adequate NPSH margin. The remaining of these three headings, "REC-DEBRIS-LF," represents the possibility that debris-related recirculation loss could be recovered. Again, the branches underneath the "RECIRC-NPSHMLF" and "REC-DEBRIS-LF" were not developed because potential success of these events is highly plant-specific, and thus, it is not feasible to develop generic estimates for the likelihood of success/failure.

The addition of debris-related headings results in the 10 LOFW sequences in the event tree. In Sequence 1, feed and bleed (PORV opened), ECCS injection, containment spray injection, ECCS recirculation, and containment spray recirculation are all successful. Also, debris effects are benign as sufficient NPSH margin is maintained for the ECCS recirculation pumps. As a result, the core cooling is successful.

Sequence 2 is similar to Sequence 1, except that debris effects are sufficiently severe that the ECCS recirculation pumps have insufficient NPSH margin. Assuming no credit for recovery actions or pump operation with insufficient NPSH margin, core damage results.

In Sequence 3, feed and bleed (PORV opened), ECCS injection, containment spray injection, and ECCS recirculation are successful, but containment spray recirculation fails. For plants having a subatmospheric containment (and possibly other designs, such as CE plants), failure of containment spray results in loss of heat removal with the result that core cooling fails during the recirculation mode. In other plant designs where the core cooling systems have their own dedicated heat exchangers, loss of containment spray recirculation does not fail core cooling. Thus, core damage occurs for the subatmospheric designs. Because debris effects are benign, core cooling is adequate for the other plant designs.

Sequence 4 is similar to Sequence 3, except that debris effects are severe enough that the ECCS recirculation pumps have insufficient NPSH margin. Assuming no credit for recovery actions or pump operation with insufficient NPSH margin, core damage results.

Sequence 5 involves successful feed and bleed (PORV opened), ECCS and containment spray injection, but subsequent failure of ECCS recirculation (for reasons other than debris). Core damage occurs as a result.

In Sequence 6, success of feed and bleed (PORV opened), success of ECCS injection, and failure of containment spray injection are followed by successful ECCS recirculation. Debris effects are benign as sufficient NPSH margin is maintained for the ECCS recirculation pumps. Per Assumption 7, containment spray recirculation also is assumed to have failed given failure of containment spray injection. For plants having a subatmospheric containment (and possibly other designs, such as CE plants), failure of containment spray results in loss of heat removal with the result that core cooling fails during the recirculation mode. Thus, core damage occurs for the subatmospheric designs. Because debris effects are benign, core cooling is adequate for the other plant designs.

Sequence 7 is similar to Sequence 6, except that debris effects are severe enough that the ECCS recirculation pumps have insufficient NPSH margin. Assuming no credit for recovery actions or pump operation with insufficient NPSH margin, core damage results.

Sequence 8 involves successful ECCS injection combined with failure of containment spray injection and failure of ECCS recirculation (for reasons other than debris). Core damage occurs as a result.

In Sequence 9, ECCS injection fails, resulting in core damage.

Finally, in Sequence 10, operators are unsuccessful in opening a PORV to support feed and bleed cooling. This failure results in core damage.

3.5.3 LOFW Mitigation

There are two possible plant-specific strategies to recover from loss of the ECCS sump from debris during a LOFW transient.

1. Continue injection, or
2. Restore the ability to recirculate from the sump.

To continue injection, a source of borated water must be found and lined-up for use, and concerns with overfilling the containment with water must be addressed. Also, the complexity of reswitching the ECCS from recirculation back to injection should be evaluated.

To restore the ability to recirculate from the sump, it may be possible to restore the NPSH margin by decreasing the flow through the sump. Spray pumps and one train of ECCS pumps could be turned off or throttled (if possible). For plants in which sprays provide heat removal, turning off all spray trains would not be acceptable.

For LOFW, another possible strategy would be to turn off train(s) of containment spray during the injection mode of feed and bleed, which would reduce the amount of debris transported to the sump, thereby reducing the likelihood of loss of NPSH margin.

Also, if feedwater could be recovered, feed and bleed could be terminated, thereby obviating the need to use the containment sump for core cooling.

4.0 QUANTIFICATION OF NEW EVENTS

Numeric evaluation of the event trees to obtain estimates of the average CDF require that branch fractions between failure and success be defined for each event in the accident sequences. These fractions are simply the probabilities that each event will or will not occur given all the precursor events that define a current plant status. Because the event probabilities usually depend on the particular accident sequence (i.e., the path taken through the event tree) and on the presumed occurrence of the initiating event, they are referred to as "conditional probabilities." This section (1) develops the conceptual framework needed to define quantitative, comparative values of conditional sump-failure probability using qualitative information and engineering judgment and (2) explains how this rationale was applied to each of the parametric case studies that contribute to the industry-wide risk assessment.

4.1 Conceptual Development of Conditional Sump-Failure Probabilities

All event trees in this study have explicitly included an event called "Probability of Loss of ECCS Recirculation NPSH Margin" so that the effects of debris generation and transport on the CDF can be estimated. These conditional probabilities also must be quantified before the event trees can be evaluated. To simplify the nomenclature in this section, this event will be referred to as the "conditional sump-failure probability." Although the complete event sequence heading more generally refers to all possible mechanisms for loss of the ECCS system, the information available for conditional probability estimates focuses exclusively on loss across the recirculation sump screen of the pressure head that is needed to provide adequate water flow.

A methodology for semiquantitative assignment of sump-failure probabilities on a plant-by-plant basis was presented in the companion report "Parametric Evaluations for PWR Recirculation Sump Performance" (Ref. 1). To summarize briefly, the parametric study examined the vulnerability of various sump configurations to blockage by different combinations of fibrous and particulate debris. Each sump configuration, or "case study," was defined using the best information available to represent an operating PWR, and iterative head-loss calculations were made to determine all debris loadings that cause pressure drops exceeding the plant-specific sump-performance criterion. The combinations of debris on the sump screen that lead to failure define a transition called the Failure-Threshold Debris Loading (FTDL) function. An example FTDL is shown in Figure 4.1 as the approximately h-shaped line. Note that the FTDL separates the range of sump performance into an area of continued recirculation with partial blockage and an area of sump failure with unacceptably high debris blockage.

The parametric evaluation also considered plant-specific information to estimate the amount of fibrous and particulate debris that might be generated or entrained by a given LOCA and be transported to the sump screen through the containment building and through the containment pool. Acknowledged uncertainties in the final transport fraction depended heavily on the activation of containment sprays that can wash material down to the recirculation pool and enhance transport to the sump because of the increased water flow demands. Other features that affect transport include the location of the sump relative to the break, the containment floor geometry, the initial size distribution of debris, and the vertical location of the break. These factors were treated parametrically by defining a "favorable" (lower) transport fraction that minimized the chance of blockage and an "unfavorable" (higher) transport fraction that enhanced the chance of blockage. Both the upper and lower estimates were chosen to be representative of actual plant conditions and not of conservative regulatory bounds. Similar ranges were defined for other parameters that affected the head-loss calculations so that both favorable and unfavorable FTDL performance curves were generated.

Example ranges of debris quantities that could reasonably be expected to transport to the sump are shown as the dashed, shaded boxes in Figure 4.1. Note that the left and right sides of the regions define the favorable and unfavorable

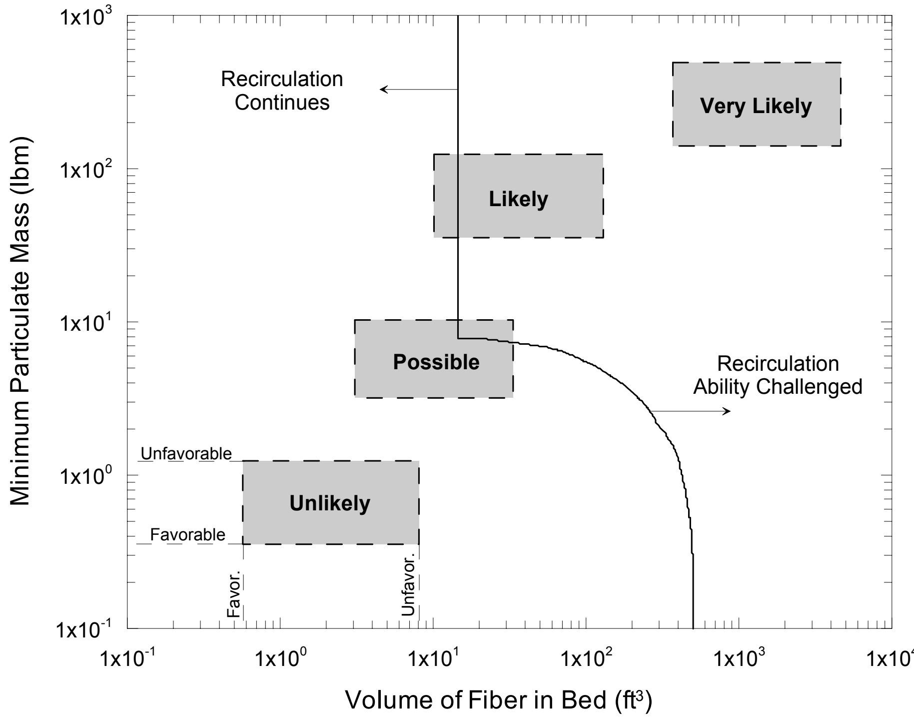

Figure 4.1 Examples of Qualitative Assignment of Conditional Sump-Failure Probabilities Developed in "GSI-191 Parametric Evaluations for PWR Recirculation Sump Performance" (Ref. 1)

volumes of fibrous debris, respectively, and the bottom and top sides define the favorable and unfavorable estimates of particulate mass, respectively. Depending on the insulation composition, the presence of sprays, and the sump configuration of the case study (defined by the recirculation flow and the screen area), the debris-transport box may lie anywhere in the sump performance space separated by the FTDL curve. Appendix B of the parametric evaluation presents these comparisons for all case studies under several assumed flow rates that correspond to large-, medium-, and small-LOCA plant responses.

Initial judgments regarding conditional sump-failure probabilities were made in the parametric study by comparing the region of potential debris transport with the failure curve as shown in Figure 4.1. Potential debris transport areas that lay to the far right of the FTDL were given a qualitative failure probability of **Very Likely**, and debris transport areas that lay to the far left of the FTDL were given a qualitative failure probability of **Unlikely**. Intermediate cases received the qualitative designations of **Possible** and **Likely,** depending on the fraction of the transport region on each side of the failure curve and on engineering judgment factors such as the location of the sump and the amount of calcium silicate in containment. The task at hand is to translate (or map) the qualitative sump-failure probability assignments onto a quantitative scale that can be propagated through the event trees. These assignments ultimately will be based on examination of results like Figure 4.1 that are presented in Ref. 1 for each parametric case study.

Some analysts will take immediate exception to the use of words such as "very likely" and "possible" to represent sump-failure probabilities. Admittedly, there is no suite of simulations or database of past accidents with which to estimate a frequentist probability in terms of proportional failure that can be used to calculate percentiles of a distribution that correspond to the adjectives. Indeed, at present, there is not even a comprehensive physical model of debris generation and transport that could be exercised in such a manner. However, these same analysts cannot deny that the calculated location of the debris-transport ranges relative to the FTDL function is a strong indication of either safety margin or vulnerability for each case study. For example, if a particular sump condition fails (all expected debris quantities to the right of the FTDL) even under favorable head-loss and transport assumptions, this is a stronger conclusion than if the expected debris range spans the FTDL. Thus, the confidence one may place in conclusions drawn from calculations like those plotted in Figure 4.1 increases with increasing distance of the debris-transport box from the FTDL.

The quantitative analyses represented by Figure 4.1 were designed to separate modeling issues associated with debris generation and transport from those associated with sump-screen head loss so that the variability inherent in the parameters of each could be examined independently. When the variability in a given parameter is understood or well characterized, it can sometimes be described quantitatively by a probability distribution and treated as an aleatory component that can be sampled appropriately in a parametric evaluation. Residual variations in a complex model that are thought or known to exist but are not well described by the distributions defined for each of its parameters then are grouped in a broad category called "state-of-knowledge uncertainty." This category dominates the variations examined by the parametric study, and it includes factors such as (1) the location of insulation in containment, (2) the effects of exact containment geometry on debris transport, (3) the particular head-loss effects induced by calcium-silicate particulates, (4) the representative size distribution of generated debris, and (5) the time dependence of debris-transport fractions over the duration of the accident scenario, among others.

In light of these large state-of-knowledge uncertainties that cannot be quantified, favorable and unfavorable values were selected for the more important parameters to represent a reasonable, or plausible, range of conditions. Nevertheless, the uncertainties in computed quantities like the expected debris transport and the sump-failure debris loadings are known to extend beyond these ranges in a manner shown conceptually in Figure 4.2. Here, the gray bands illustrate extended ranges that might be occupied by estimates of debris transport (dashed boxes) and the FTDL (solid curve). If more information was available to describe distributions of the individual input parameters, it might be possible to generate distributions on the calculated quantities similar to those superimposed in Figure 4.2.[6] This would open numerous avenues for numerical quantification of the failure probability, but unfortunately, this information does not exist. The only recourse for quantification is to examine the "quality" of the information and the perceived "fidelity" of the physical models used in the analyses.

For example, debris transport tests in complex pool geometries consistently showed transport fractions in water of between 10% and 25%; limited two-phase debris generation tests helped to estimate the fraction of fine debris, and engineering calculations were used to estimate the debris washdown fractions with and without containment sprays. This combination of experimental observation and engineering judgment lends some confidence that favorable and unfavorable debris transport fractions lie somewhere near the 40th and 60th percentiles of the underlying state-of-knowledge uncertainty distribution (narrow debris transport ranges). In contrast, for some parametric cases, the debris compositions were completely unknown, and broad industry-wide variations for fiber volume were assigned that might represent the 10th and 90th percentiles of uncertainties at the corresponding plant (wide debris transport ranges). Figure 4.2 shows two distributions for debris-transport quantities that represent an estimate of range based on good information and an estimate based on poor information. It is apparent that information quality affects the spread, or standard deviation, of the uncertainty distribution.

Building on the conceptual framework of underlying but unknown uncertainty distributions for debris transport and the FTDL, it is clear that

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6 Note that one-dimensional normal distributions have been plotted in log-log space only to illustrate a concept. Properly generated output distributions would actually be two-dimensional and would be highly asymmetric (non-Gaussian) for the FTDL.

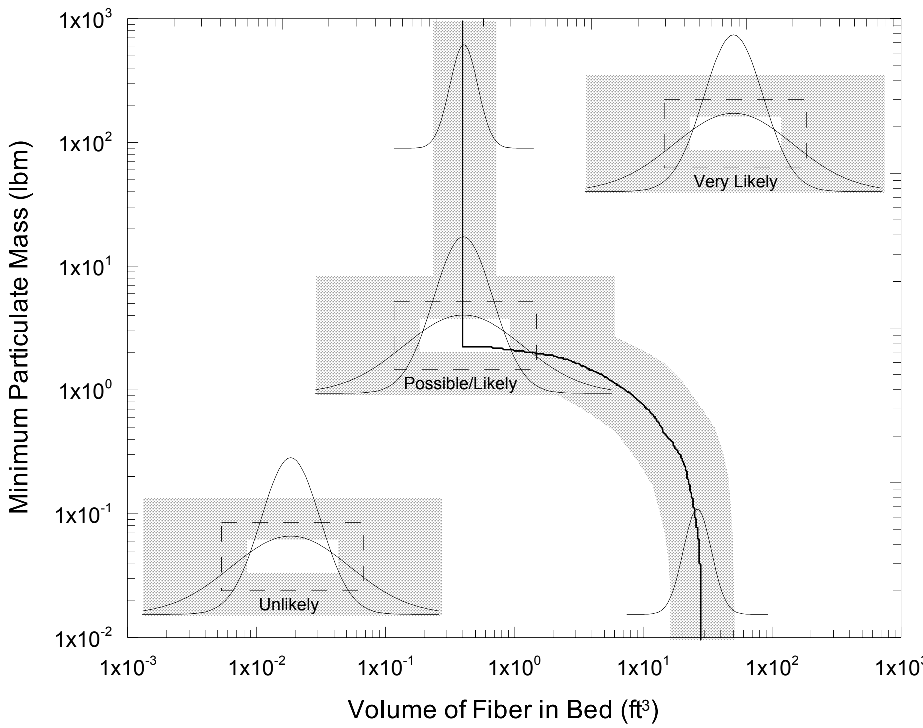


Figure 4.2 Conceptual Illustration of State-of-Knowledge Uncertainty Surrounding the Computed FTDL (Solid Line) and the Debris Transport Ranges (Dashed Boxes)

a quantitative estimate of conditional sump-failure probability (i.e., the probability of debris transport greater than the FTDL) implies a convolution integral of two probability distributions. More intuitively, one may think about the amount of overlap between the two distributions. When the distance between them is great, only the tails overlap and the conclusion is definitively either sump failure or continued operation depending on which side of the FTDL the debris transport range lies. It is also evident that the separation distance, and hence the degree of confidence one may place in the methodology of the parametric evaluation, also increases with the quality of the information and the fidelity of the available physical models. This is because better information (less variability) decreases the amount of overlap for a given location of the two distributions.

4.2 Definition of Conditional Sump-Failure Probabilities for Parametric Case Studies

All prior discussion prepares for the original task of calibrating a quantitative scale to the qualitative comparisons provided by the parametric evaluation. However, at this point, a conceptual basis has been established for the use of conditional probability statements, and it should be apparent that the adjectives of **Unlikely**, **Possible**, **Likely**, and **Very Likely** were chosen in the parametric evaluation simply to express the degree of comparison between implicit uncertainties that are centered on debris transport estimates and sump-screen head-loss calculations. These words represent an intuitive understanding of state-of-knowledge uncertainties in the vulnerability assessment process, and they convey the relative strength of the conclusions reached for each case study. Further examination of the decision process and the information quality is needed to set constraints (calibration points) on the numerically equivalent conditional probabilities. This will lead to a set of guidelines for reevaluating the debris transport and head-loss figures presented in the parametric study and for assigning quantitative sump-failure probabilities to each ECCS recirculation event in this risk assessment.

Quantitative probability assignments arrived at by a synthesis of information from calculations and testing rather than from a counting frequency analysis of observed events are sometimes called “subjective” or “Bayesian” probabilities. Differences in the definitions and interpretations of probability theory posed by the so-called “frequentist” and “Bayesian” schools of thought often can stimulate discussions of theological proportions. However, the practical application and relevance of a conditional probability arrived at by either approach are largely identical. The term “conditional probability of failure” in this report refers to the relative chance of ECCS failure vs successful ECCS operation for a *single* postulated accident. It was suggested above that quantitative values could be computed if underlying variabilities were well characterized; however, they are not, so the assignments made here express the confidence or “degree of belief” that one has in a conclusion regarding sump failure that is supported by prior information provided in the form of engineering analysis. If many such accidents had already occurred, the number of failures could be compared with the total number of events to estimate the same probability. However, there have been few, if any, of the accident sequences postulated here, so the subjective probability assignments may be interpreted just as easily as the proportion of failures that would occur if *many* similar accidents were to take place. There is not enough evidence in the accident record to support any more than a semantic argument over which is the “proper” interpretation.

Several considerations affect the assignment of quantitative sump-failure probabilities. First, in deference to the fact that no information is perfectly complete, which implies that there will always be exceptions and outliers to every decision, no conditional sump-failure probability will be assigned a certain failure value of 1.0 or a certain success value of 0.0. Limits will be imposed for both extremes. Second, because favorable and unfavorable parameter assignments were intended to be reasonable mid-range values and because estimates of debris transport and head loss have implicit uncertainties, it is *not* appropriate to assume immediate failure or success just because the debris transport range lies slightly to one side of the FTDL or the other. This acknowledges that the implicit uncertainty distributions have width. Third, for the same reasons, conditional failure probabilities for intermediate debris transport cases that span the FTDL cannot be argued to be greatly different from 0.5. They are simply indeterminant. Numeric values of 0.4 and 0.6 will be assigned to the qualitative categories of **Possible** and **Likely**, respectively, to provide a convenient way of discriminating between them.

Further constraints on the change of sump-failure probability with distance between the FTDL curve and the debris transport range follow from examination of the figures in Appendix B of Ref. 1 in combination with the perception that the width between favorable and unfavorable parameter ranges is directly proportional to variability (spread) in the underlying uncertainty distributions. Note that the range between favorable and unfavorable FTDL estimates for a given sump configuration typically span factors of 2 to 3, whereas debris transport boxes can span more than one decade on the logarithmic plots. Thus, the width and location of the debris-transport estimates dominate the quantification of sump-failure probability. If the head-loss failure calculations were perfectly defined with no uncertainty, the sump-failure probability would simply be the integral of the debris transport distribution lying to the left of the FTDL. It is tempting to presume a functional form for the distribution of debris transport and to measure distance from the FTDL in terms of one-dimensional standard deviations that would have corresponding percentiles of failure probability, but this approach implies that more is known about the uncertainty distributions than actually can be supported. It is preferable to define a comparatively wide uncertainty whose probability integral falls by some factor that matches one’s perception of likelihood for every increment away from the mean, for example, a factor of 10 reduction in probability for every factor of 10 increase in distance away from the expectation.

Perception of likelihood can differ between personal and societal perspectives, but at least one example of a subjective likelihood scale that has been defined to correspond with conditional probability assignments for use in nuclear-power safety analyses is provided in Table 4.1 (Ref. 7). This scale was formulated for Level-2 PRA applications where the possible outcomes of severe reactor accidents are dominated by state-of-knowledge uncertainties. The scale matches nonuniform probability intervals with

Table 4.1 Guidelines for Assigning Conditional Probabilities to Events with "State-of-Knowledge" Uncertainty (Ref. 7)

VALUE	DESCRIPTION
1.	The indicated outcome is **CERTAIN** given the conditions defined by the case in question. Usually this is reserved for logical outcomes not requiring analysis to support them. Analysis or calculations that are needed to support a certain outcome use only methods appearing in textbooks or peer-reviewed journals. The results of the analysis demonstrate the indicated outcome to be appropriate considering all relevant uncertainties. Other analysis approaches have been considered, and these either yield the same result or are not applicable. No debate as to the outcome would be expected from individuals who are informed of the specifics of the case and the associated phenomena.
1. - 1.0E-3 **(i.e., 0.999)**	The indicated outcome is **ALMOST CERTAIN**. Detailed analysis has been performed that includes all phenomena identified as relevant and has been subjected to independent review. At least one other individual who has analyzed the situation [other than the analyst and reviewer(s)] agrees that the outcome is almost certain. Separate analysis exists that supports this outcome. Consideration of all identified uncertainties has been made, and none has been found to have a credible effect on the outcome.
(1. - 1.0E-2) **i.e., 0.99**	The indicated outcome is **EXTREMELY LIKELY**. Either detailed analysis has been performed and subjected to independent review or a significant body of directly applicable experimental data published in the technical literature supports this position. The indicated outcome is obtained for all credible assumptions as to the values of parameters in supporting analysis. Arguments against this position are not supported by either analysis or data.
(1. - 5.0E-2) **i.e., 0.95**	The indicated outcome is **VERY LIKELY**. Either detailed analysis has been performed and reviewed for completeness or a significant body of relevant experimental data supports this position. Arguments against this position are obviously flawed or data exist that contradict the arguments presented in some measure.
0.9	The indicated outcome is **LIKELY**. Either it is supported by analysis or the preponderance of experimental evidence points to this result. Arguments against this position are apparently flawed, and the technical basis for disagreement with the counter argument has been established. Alternatively, no analysis has been performed, but there is general agreement between two or more independent individuals knowledgeable of the situation that the indicated outcome is appropriate.
0.5	The indicated outcome is fully **POSSIBLE**. Either no analysis has been performed or existing analysis is inconclusive. Inconclusive analysis includes that for which no concurrence from an independent party can be gained. Experimental data do not clearly indicate this outcome to be more likely or experiments are obviously no directly pertinent.
0.1	The indicated outcome is **UNLIKELY**. It cannot be supported by incontrovertible analysis or a preponderance of data. However, it is a credible outcome when attendant uncertainties are considered.
5.0E-2	The indicated outcome is **VERY UNLIKELY**. Analysis cannot rule it out completely. However, arguments in favor of this outcome are not supported by the available data. At most, a few experiments suggest that this outcome could occur.
1.0E-2	The indicated outcome is **EXTREMELY UNLIKELY**. Uncertainties in the available analysis that show the outcome not to occur can be identified. Consideration of these uncertainties might lead to this outcome, but no analytical or experimental support can be found.
1.0E-3	The indicated outcome is **ALMOST IMPOSSIBLE**. It has credibility only if a number of unsupported (but not demonstrably incorrect) assumptions are made. No analysis is available to support this result even when relevant uncertainties in the parameters of the analysis are considered.
0.	The indicated outcome is **IMPOSSIBLE**. It is either ruled out by the physical situation or a large body of analysis and experiments support alternate outcomes.

statements of confidence regarding the outcome of an event that range from **Impossible** (probability 0.0) to **Certain** (probability 1.0). A good generic discussion of the experimental and/or computational evidence that is needed to support each designation also is provided. It should be noted that it is common to assign a subjective probability of 0.5 for inconclusive cases that are considered plausible but that cannot be refuted or supported by additional evidence.

A classification scheme similar to that suggested in Table 4.1 was developed to translate qualitative impressions of sump-failure probability from the parametric study into numerically equivalent conditional probabilities. It is based on comparing the separation distance to the right or left of the debris-transport range from the FTDL curves for each case study presented in Appendix B of the parametric evaluation. Table 4.2 lists the distance criteria applied to each quantitative assignment, and Figure 4.3 presents them graphically to illustrate how the individual comparisons were performed. Note that the probability increments are symmetric for equivalent locations on each side of the FTDL and that horizontal distances are measured from the nearest edge of the box to the sump failure curve. Occasionally, the debris transport range for a case study categorized as **Very Likely** will have a vertical distance from the "knee" of the FTDL that is closer than the nearest horizontal distance. No special considerations or exceptions were granted for these cases because it was felt that, in general, the favorable estimates of particulate mass are quite low.

The probability bins adopted here change in roughly linear increments between 0.1 and 0.9 for indeterminant cases near the FTDL and in logarithmic increments across the more definitive cases with qualitative assignments of **Unlikely** and **Very Likely**. This selection softens the approach to a certain outcome by extending the tails of the uncertainty distribution at each extreme, but it maintains a relatively sharp transition between success and failure within a factor of 10 below and above the failure criterion. These definitions of quantitative conditional sump-failure probabilities are consistent with the philosophy suggested by the example given in Table 4.2, and they provide a convenient "factor of 10" unit of comparison for visual assessment of the sump vulnerability figures.

The categories of **Possible** and **Likely** were assigned values of 0.4 and 0.6, respectively, based on the degree of overlap to the left and right of the FTDL. To maintain some consistency with qualitative vulnerability assignments that were upgraded because of additional considerations, these special cases were given values one level higher in Table 4.2 than the location of the debris-transport box alone would prescribe. In most cases, this meant a conditional probability assignment of 0.9. Additional assumptions required to quantify the conditional sump-failure probability for each event sequence in the risk assessment are presented in Attachment B of this report.

Table 4.2 Numeric Equivalents of Qualitative Conditional Probability Assignments

Qualitative Assignment	Conditional Probability	
Very Likely	0.9	if debris transport box < 10 to right of FTDL curve
	0.99	if debris transport box < 100 to right of FTDL curve
	0.999	if debris transport box > 100 to right of FTDL curve
Likely	0.6	if debris transport box is mostly to the right of the FTDL
Possible	0.4	if debris transport box is mostly to the left of the FTDL
Unlikely	0.1	if debris transport box < 10 to left of FTDL curve
	0.01	if debris transport box < 100 to left of FTDL curve
	0.001	if debris transport box > 100 to left of FTDL curve

Notes: Comparisons of debris transport with the FTDL refer to the left-hand edge of the box for the category of **Very Likely** and to the right-hand edge for the category of **Unlikely**.

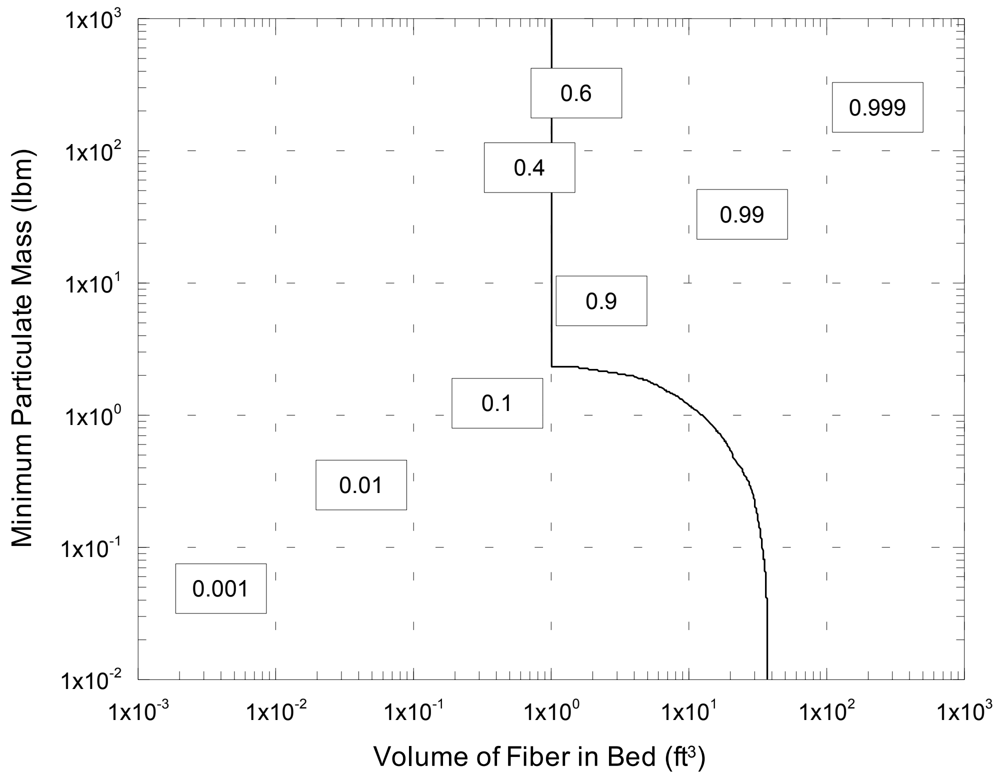


Figure 4.3 Quantitative Conditional Sump-Failure Probabilities Illustrated by Comparison of the Expected Debris-Transport Ranges (Boxes) and the FTDL Failure Condition (Solid Curve)

5.0 RESULTS

The results of this study are shown in Figure 5.1, which shows the total CDF[7] (with and without contributions from debris-induced failure of recirculation sump flow) for each of the 69 parametric cases examined in the parametric evaluation report [1]. The results are shown using traditional initiating event frequencies for LOCAs (upper figure) and using LOCA initiating-event frequencies based on the leak-before-break assumption (lower figure). The total CDF is shown to increase by a factor of 2 to 4 for a few cases; however, the majority of cases are shown to increase by an order of magnitude or more.[8]

Another way to display these results is shown in Figure 5.2, which indicates the effect of debris-induced loss of the recirculation sump on CDF in the form of a ratio: Modified CDF/Baseline CDF. Thus, it represents the factor by which the CDF would increase if debris-induced sump failure were included in a PRA model. Because the ratio is somewhat sensitive to the actual value of CDF, results are shown for estimates made using the traditional and leak-before-break initiating event frequencies. Although the values for the CDF ratio differ because of this effect, the overall increment is clearly shown to be large for a substantial number of cases.

The range of CDF ratios shown in Figure 5.2 spans a considerable range without an obvious trend. However, the number of cases with relatively high CDF ratios is roughly the same as the number with small ratios. The *average* increase in CDF (across all 69 cases) from debris-induced failure of the recirculation sump is approximately 100 using traditional LOCA initiating-event frequencies and 45 using the leak-before-break frequencies.

The contribution of each type of accident sequence to the estimated CDFs is indicated in Table 5.1. This table lists the baseline and modified CDF associated with each of the accident sequences described in Sec. 2 averaged over the entire population of U.S. PWRs.[9] Again, values are shown using the traditional and leak-before-break LOCA initiating-event frequencies. Two observations can be made from this table. First, LOCA events dominate the estimated *increase* in CDF (i.e., stuck-open PORV and LOFW events are not significantly affected by the issue). Second, the largest increase in CDF (measured by CDF ratio) occurs in small-break LOCAs. It should be noted that small-break LOCAs are also events in which recovery actions are most likely to be effective, and thus, more detailed plant-specific evaluations are likely to show much smaller increases in CDF for these sequences.

The extent to which individual plant design features contribute to the estimated increase in CDF were examined by generating “scatter plots” that show total CDF ratio as a function of parameter values. For example, Figures 5.3 through 5.5 show how the CDF ratio varies with case-specific values of sump screen area, NPSH margin, and the amount of calcium-silicate in the containment (expressed as a percentage of all piping insulation), respectively. No clear trends are indicated in any of these figures; i.e., CDF increments are not directly correlated to any of the parameters individually. In other words, small sump-screen area (by itself) does not necessarily indicate a high sump failure probability, and large sump-screen area (by itself) does not necessarily indicate immunity from excessive debris-induced head loss.

7 “Total” in this context represents the arithmetic sum of the frequencies of the six classes of accident sequences examined in this study. The “total” does not include contributions of accident sequences not requiring recirculation cooling to mitigate the initiating event.

8 Recall that these results do not credit the possibility that ECCS pumps continue to function with loss of NPSH margin nor are operator recovery actions to restore core cooling when normal recirculation flow terminates. Such considerations are highly pump-design-specific and plant-specific, respectively, and beyond the scope of this study.

9 These values represent the sum of the sequence CDF for each of 69 cases divided by the number of cases.

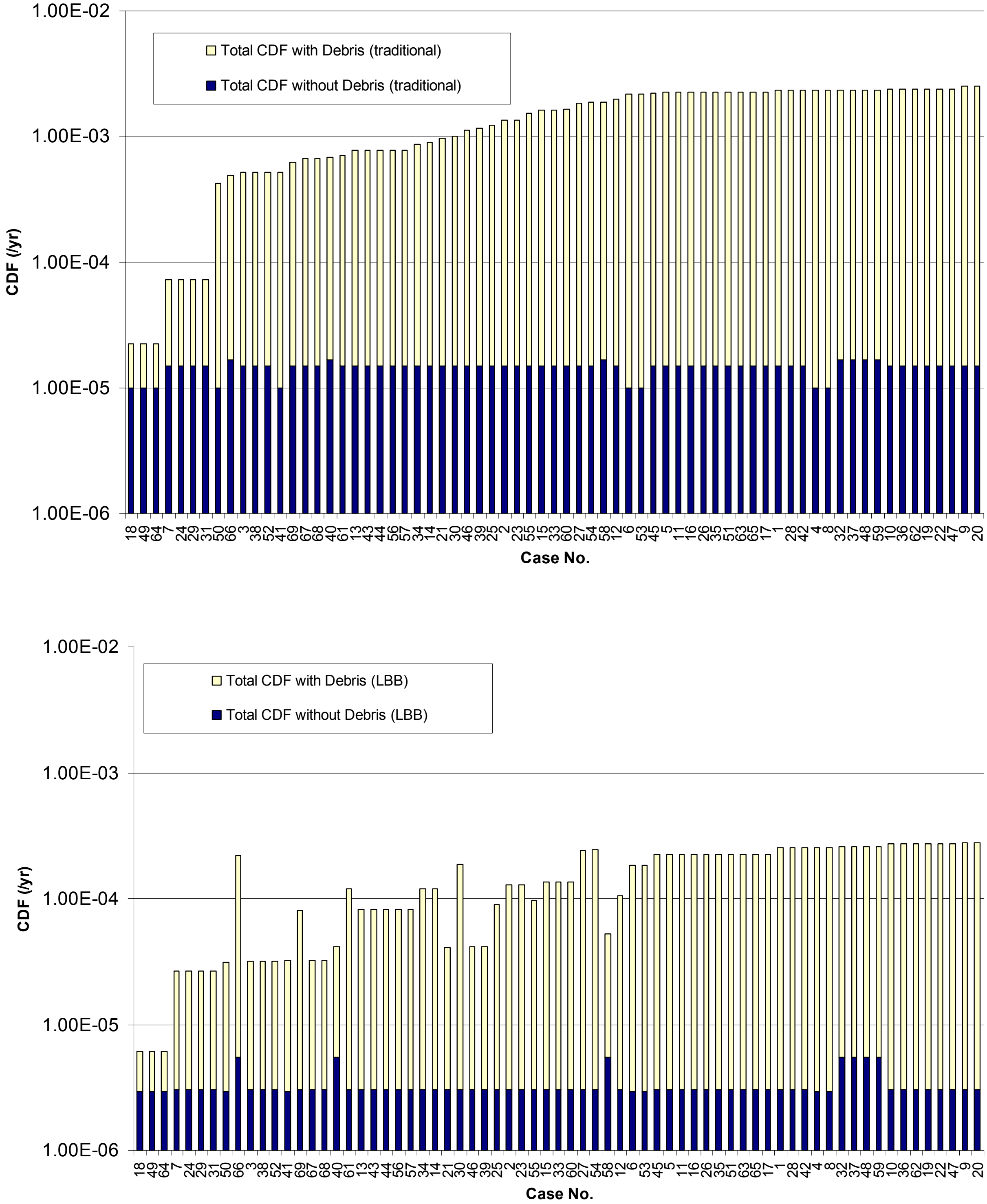
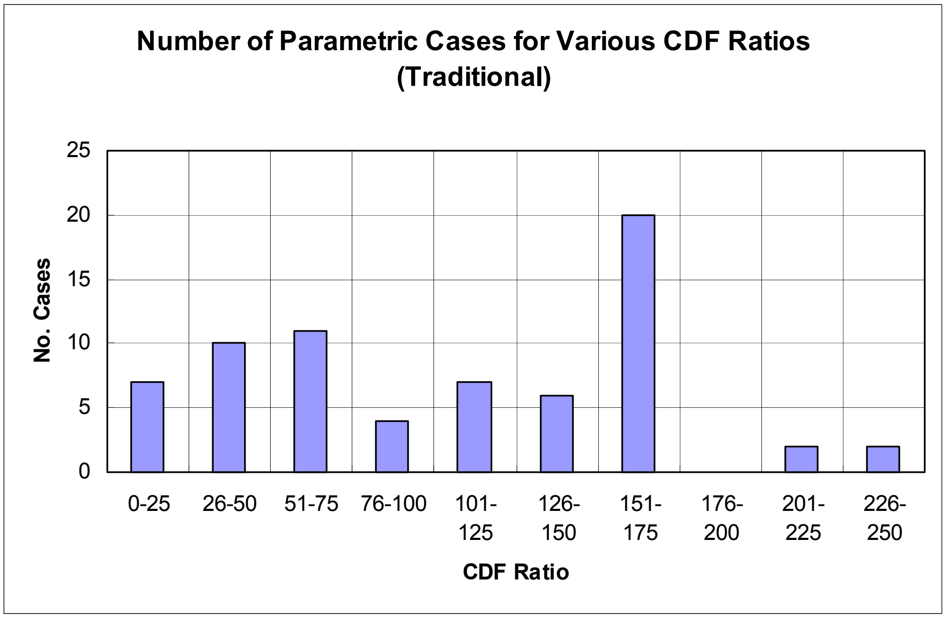


Figure 5.1 Change in CDF from Debris-Induced Loss of Recirculation Sump Flow
[Based on traditional LOCA initiating event frequencies (top) and
leak-before-break initiating event frequencies (bottom)]



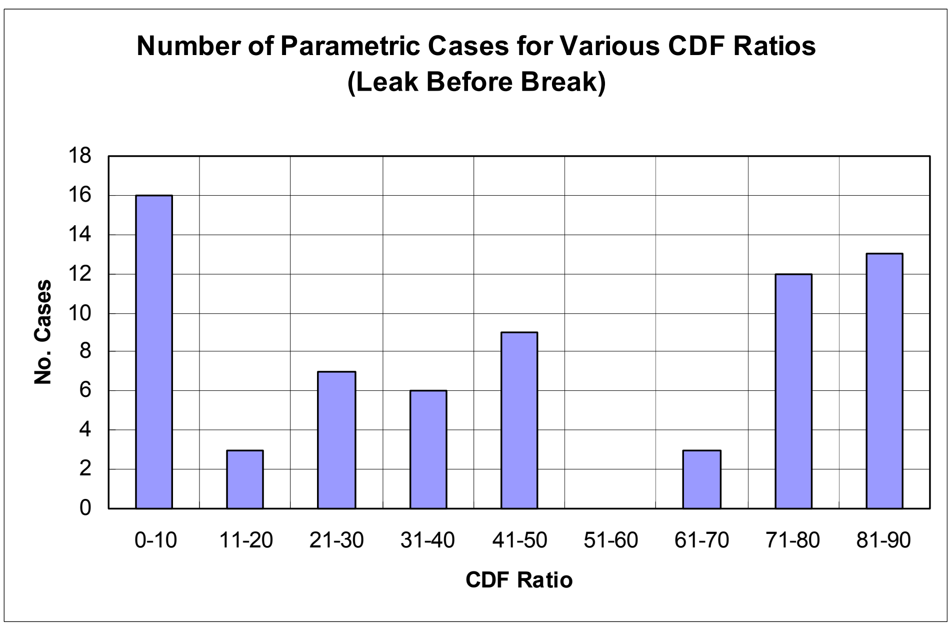


Figure 5.2 Effect of Debris-Induced Loss of Recirculation Sump Flow on CDF Expressed in Terms of CDF Ratio: Modified CDF/Baseline CDF
Results shown for Baseline CDF Using Traditional and Leak-Before-Break LOCA Initiating Event Frequencies.

Table 5.1 Contributions of Each Accident Sequence to the Baseline and Modified CDF

Traditional LOCA I.E. frequencies	***Large LOCA***	***Medium LOCA***	***Small (S3) LOCA***	***Very-Small (S2) LOCA***	**PORV**	***LOFW***	***TOTAL***
With debris	4.1E-04	5.3E-04	2.6E-04	2.6E-04	9.6E-06	8.5E-07	1.5E-03
No debris	3.6E-06	6.1E-06	1.1E-06	1.1E-06	2.2E-06	4.2E-07	1.4E-05
ΔCDF	4.1E-04	5.2E-04	2.6E-04	2.6E-04	7.4E-06	4.3E-07	1.5E-03
CDF ratio	113	87	238	244	4	2	101
Leak-before-Break LOCA I.E. frequencies	***Large LOCA***	***Medium LOCA***	***Small (S3) LOCA***	***Very-Small (S2) LOCA***	**PORV**	***LOFW***	***TOTAL***
With debris	2.9E-06	1.0E-05	5.8E-06	1.2E-04	9.6E-06	8.5E-07	1.5E-04
No debris	2.6E-08	1.1E-07	2.4E-08	4.8E-07	2.2E-06	4.2E-07	3.3E-06
ΔCDF	2.9E-06	9.9E-06	5.7E-06	1.2E-04	7.4E-06	4.3E-07	1.5E-04
CDF ratio	113	87	236	243	4	2	45

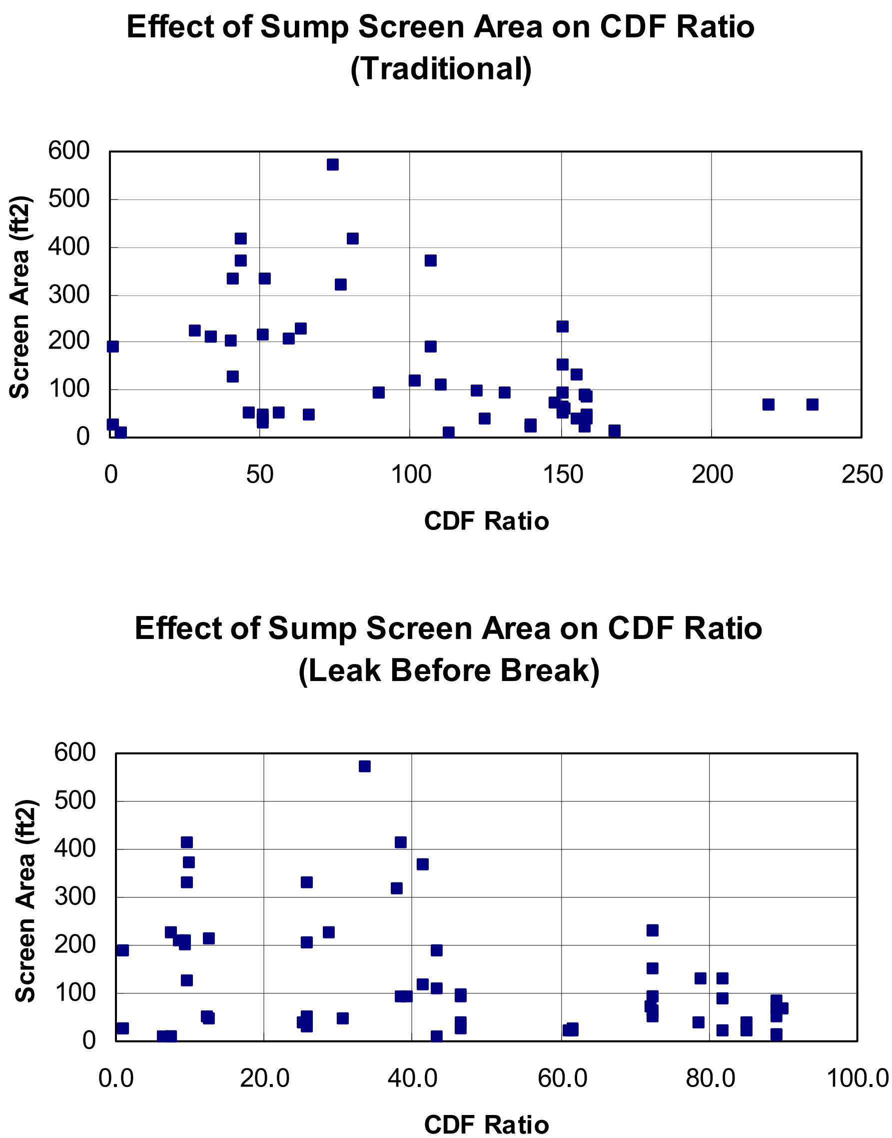
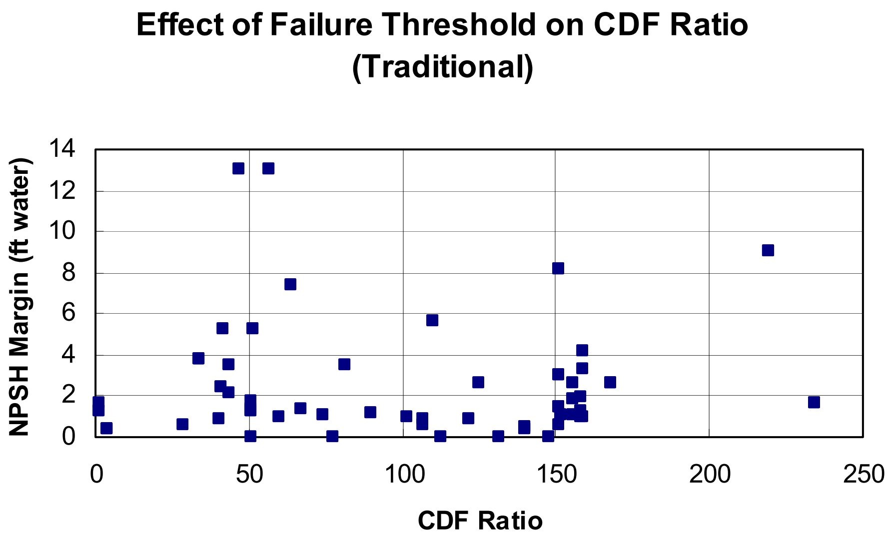


Figure 5.3 CDF Ratio Shown as a Function of Sump Screen Area (69 Cases)



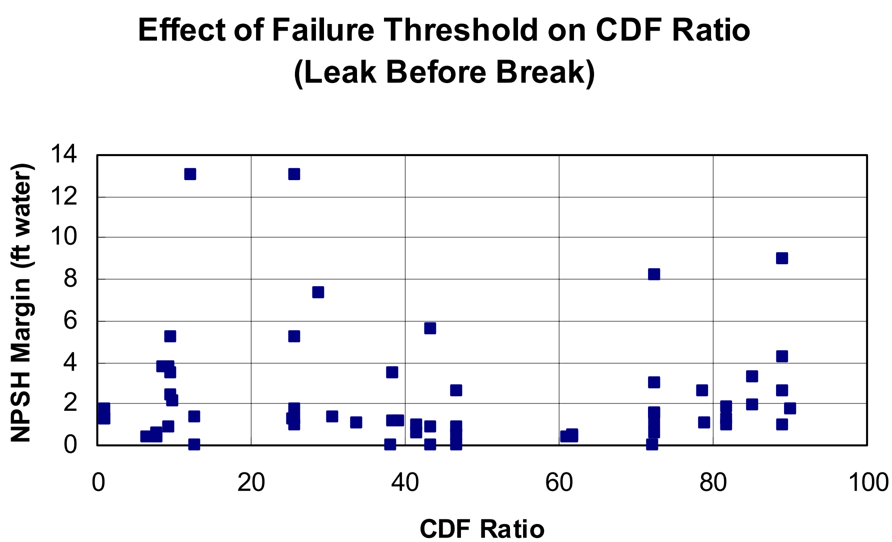
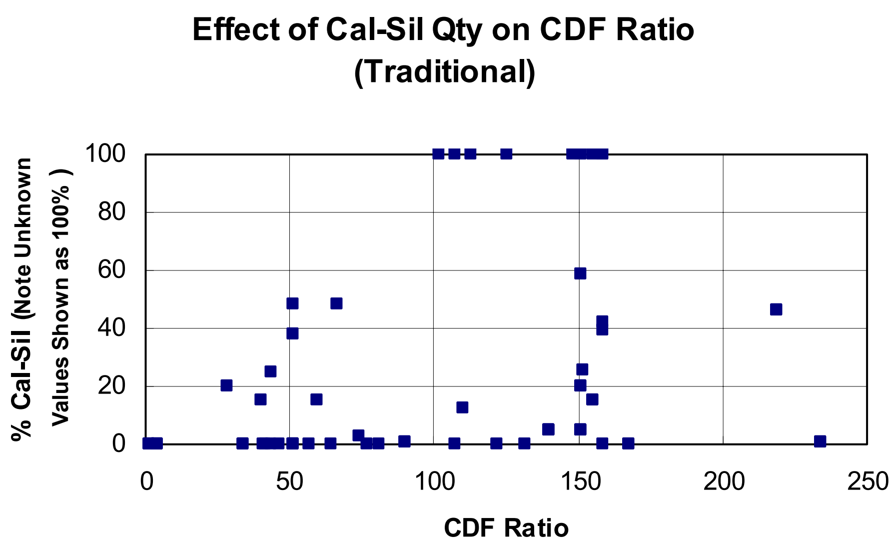


Figure 5.4 CDF Ratio Shown as a Function of NPSH Margin (69 Cases)



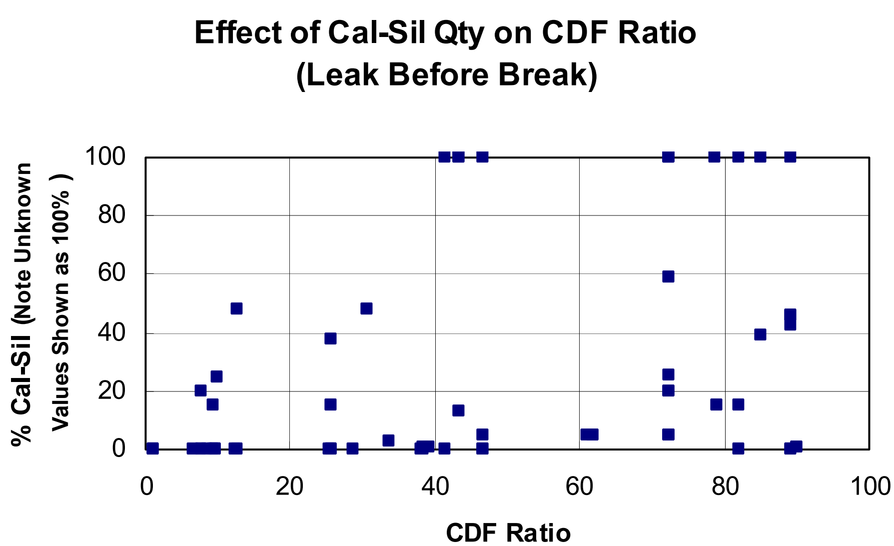


Figure 5.5 CDF Ratio Shown as a Function of Percentage of Calcium Silicate as Piping Insulation Material in Containment (69 Cases)

6.0 CONCLUSIONS

The results of parametric evaluations of PWR recirculation sump performance conducted in support of GSI-191 were used as a technical basis for estimating the conditional probability of sump failure (and thus recirculation cooling) for PWR accident sequences. This information was used to estimate the effect of debris-induced loss of NPSH margin on the CDF for the entire population of U.S. PWRs.

Results indicate that the conditional probability of recirculation sump failure (given a demand for recirculation cooling) is sufficiently high at most U.S. plants to cause an increase in the total CDF of an order of magnitude or more. Expressed in other terms, the factor by which the total core damage could increase by taking this failure mode into account was estimated to span the range of 1.0 (i.e., no change) to nearly 250 using traditional LOCA initiating-event frequencies and 1.0 to 90 using leak-before-break initiating-event frequencies. However, it is important to note that these results do not take into account the possibility that ECCS pumps might continue to function with loss of NPSH margin or that operators can take manual actions to restore core cooling if normal recirculation flow terminates. Such considerations are highly pump-design-specific and plant-specific, respectively, and beyond the scope of this study.

An examination of the major contributors to the estimated increase in CDF indicates that no *single* plant design feature is responsible for a large conditional probability of failure. Conversely, no *single* design feature safeguards a plant from the potential for excessive debris-induced head loss. These findings underscore the need for plant-specific analysis to characterize recirculation sump performance.

7.0 REFERENCES

[1] “GSI-191: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance,” LA-UR-4083, Rev. 1, Technical Letter Report, Los Alamos National Laboratory, August 2001.

[2] “Reactor Risk Reference Document,” NUREG-1150, United States Nuclear Regulatory Commission, February 1987.

[3] “Rates of Initiating Events at U.S Nuclear Power Plants: 1987-1995,” NUREG/CR-5750, Idaho National Engineering and Environmental Laboratory, February 1999.

[4] “Selection of Pressurized Water Reactor Accident Sequences for Evaluation of the Effect of Debris in the Sump,” Letter Report to NRC from LANL, Los Alamos National Laboratory, April 30, 1999.

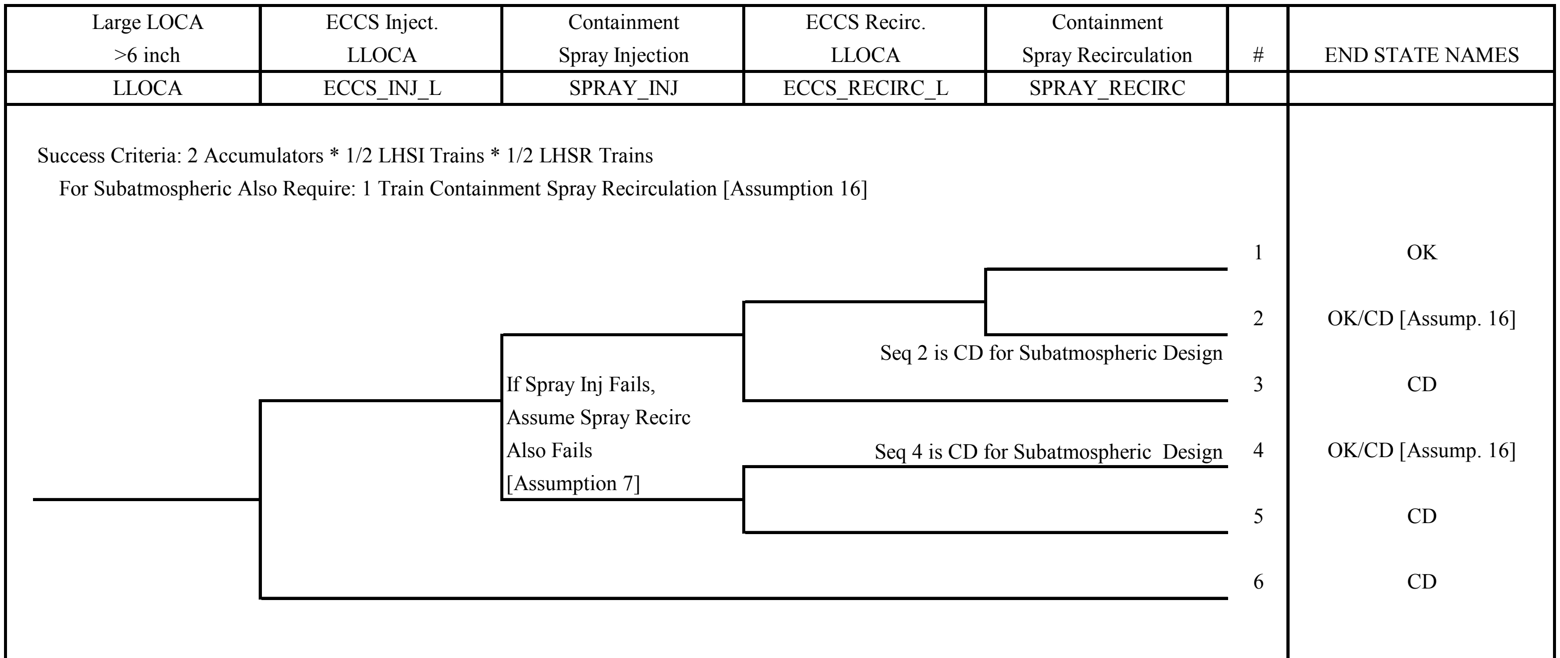
[5] “Small Break Loss of Coolant Accident Analysis for the B&W 177 FA Raised-Loop Plant in Response to NUREG-0737, Item II.K.3.31,” Babcock and Wilcox Report BAW-1981A, May 1989.

[6] SAPHIRE Version 6.68, Idaho National Energy and Environmental Laboratory.

[7] "Procedures for Conducting Probabilistic Safety Assessments of Nuclear Power Plants (Level 2)," Safety Series No. 50-P-8, International Atomic Energy Agency, Vienna 1995.

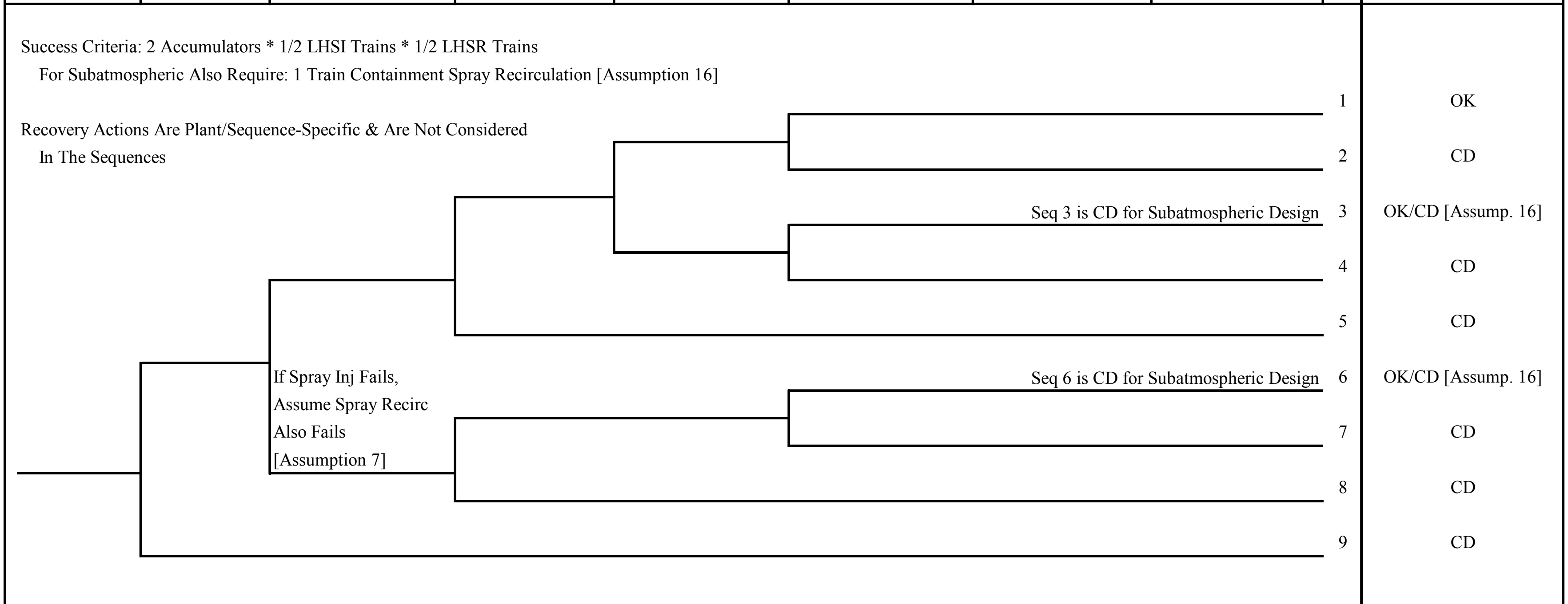
ATTACHMENT A

EVENT TREES USED FOR CORE-DAMAGE FREQUENCY ANALYSIS



LLOCA-FUNC-NO-DEBRIS - Large LOCA Functional Event Tree, PWRs In General, No Debris

Large LOCA >6 inch	ECCS Inject. LLOCA	Containment Spray Injection	ECCS Recirc. LLOCA	Containment Spray Recirculation	Avoid Loss ECCS Recirc NPSH Margin Due to Debris	ECCS Recirc with Loss NPSH Margin	Recover from loss of ECCS Recirc due to Debris	#	END STATE NAMES
LLOCA	ECCS_INJ_L	SPRAY_INJ	ECCS_RECIRC_L	SPRAY_RECIRC	DEBRIS_OK_L	RECIRC_NPSHM_L	REC_DEBRIS_L		



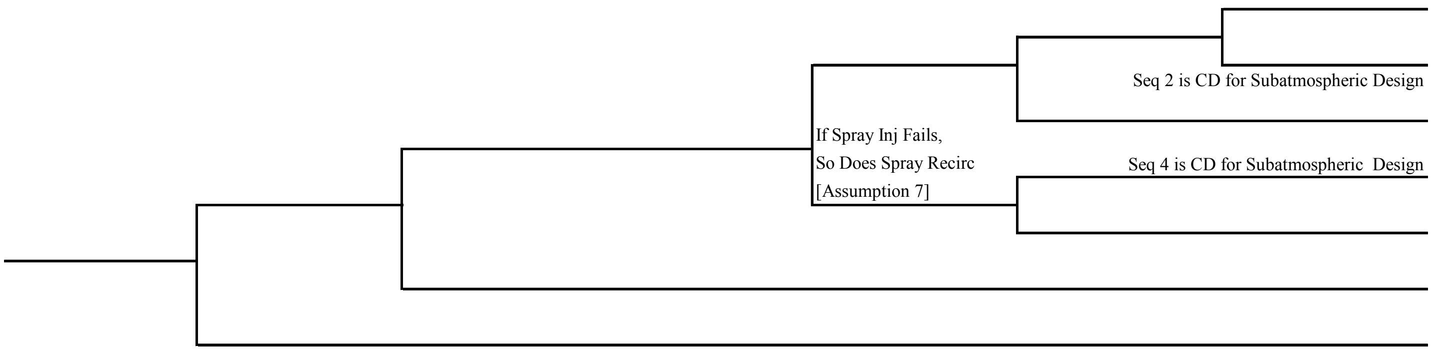
LLOCA-FUNC-WITH-DEBRIS - Large LOCA Functional Event Tree, PWRs In General, Debris

Loss of Main & Aux FW	Open PORV(s) for Feed & Bleed	ECCS Inject. SLOCA_3	Fan Coolers Prevent Ctmt Spray Actuation	Containment Spray Injection	ECCS Recirc SLOCA_3	Containment Spray Recirculation	#	END STATE NAMES
LOFW	FB	ECCS_INJ_S3	FAN_COOL	SPRAY_INJ	ECCS_RECIRC_S3	SPRAY_RECIRC		

Success Criteria: Reactor trip * (Feed & Bleed * 1/2 HHSI Trains * 1/2 HHSR Trains piggybacked on LSHR) [Assumptions 5, 12]
For Subatmospheric Also Require: 1 Train Containment Spray Recirculation [Assumption 16]

Rapid depressurization to go to RHR SDC prior to switchover from ECCS injection to recirculation is not possible with feed & bleed (no steam generator heat removal)

Use of feed & bleed discharges sufficient energy to containment (after quench tank rupture disk failure) such that spray actuation will occur even with operation of fan coolers



#	END STATE NAMES
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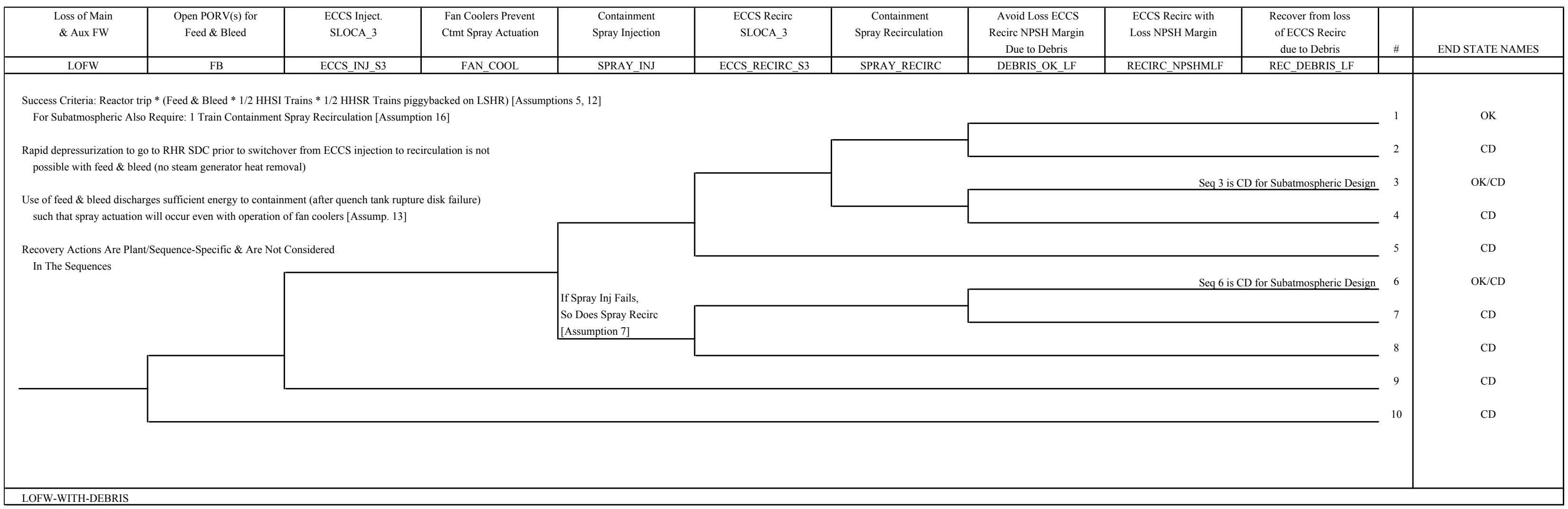
2	OK/CD [Assump 16]
3	CD
4	OK/CD [Assump 16]
5	CD
6	CD
7	CD

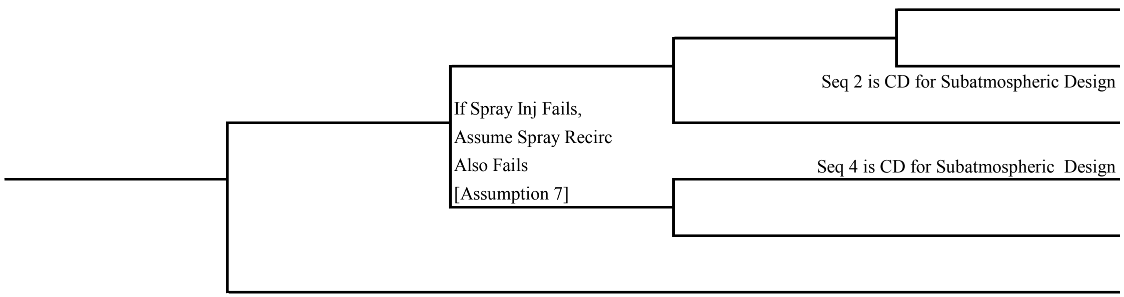
LOFW-NO-DEBRIS


Loss of Main & Aux FW
Open PORV(s) for Feed & Bleed
ECCS Inject. SLOCA_3
Fan Coolers Prevent Ctmt Spray Actuation
Containment Spray Injection
ECCS Recirc SLOCA_3
Containment Spray Recirculation
Avoid Loss ECCS Recirc NPSH Margin Due to Debris
ECCS Recirc with Loss NPSH Margin
Recover from loss of ECCS Recirc due to Debris
#
END STATE NAMES
LOFW
FB
ECCS_INJ_S3
FAN_COOL
SPRAY_INJ
ECCS_RECIRC_S3
SPRAY_RECIRC
DEBRIS_OK_LF
RECIRC_NPSHMLF
REC_DEBRIS_LF
Success Criteria: Reactor trip * (Feed & Bleed * 1/2 HHSI Trains * 1/2 HHSR Trains piggybacked on LSHR) [Assumptions 5, 12]
For Subatmospheric Also Require: 1 Train Containment Spray Recirculation [Assumption 16]
Rapid depressurization to go to RHR SDC prior to switchover from ECCS injection to recirculation is not possible with feed & bleed (no steam generator heat removal)
Use of feed & bleed discharges sufficient energy to containment (after quench tank rupture disk failure) such that spray actuation will occur even with operation of fan coolers [Assump. 13]
Recovery Actions Are Plant/Sequence-Specific & Are Not Considered In The Sequences
If Spray Inj Fails, So Does Spray Recirc [Assumption 7]
Seq 3 is CD for Subatmospheric Design
Seq 6 is CD for Subatmospheric Design
1 OK
2 CD
3 OK/CD
4 CD
5 CD
6 OK/CD
7 CD
8 CD
9 CD
10 CD
LOFW-WITH-DEBRIS

Med LOCA 4 to 6 in	ECCS Inject. MLOCA	Containment Spray Injection	ECCS Recirc. MLOCA	Containment Spray Recirculation	#	END STATE NAMES
MLOCA	ECCS_INJ_M	SPRAY_INJ	ECCS_RECIRC_M	SPRAY_RECIRC		

Success Criteria: Reactor Trip * 1 Accumulator * 1/2 HHSI Train * 1/2 HHSR Trains piggybacked on LHSR [Assumptions 5, 9, 12]
For Subatmospheric Also Require: 1 Train Containment Spray Recirculation [Assumption 16]

Cooling not required from steam generators or feed & bleed; hole sufficiently large.
Also, hole sufficiently large such that depressurization to RHR/SDC possible w/o steam generators [Assumption 15]



#	END STATE NAMES
1	OK
2	OK/CD [Assump. 16]
3	CD
4	OK/CD [Assump. 16]
5	CD
6	CD

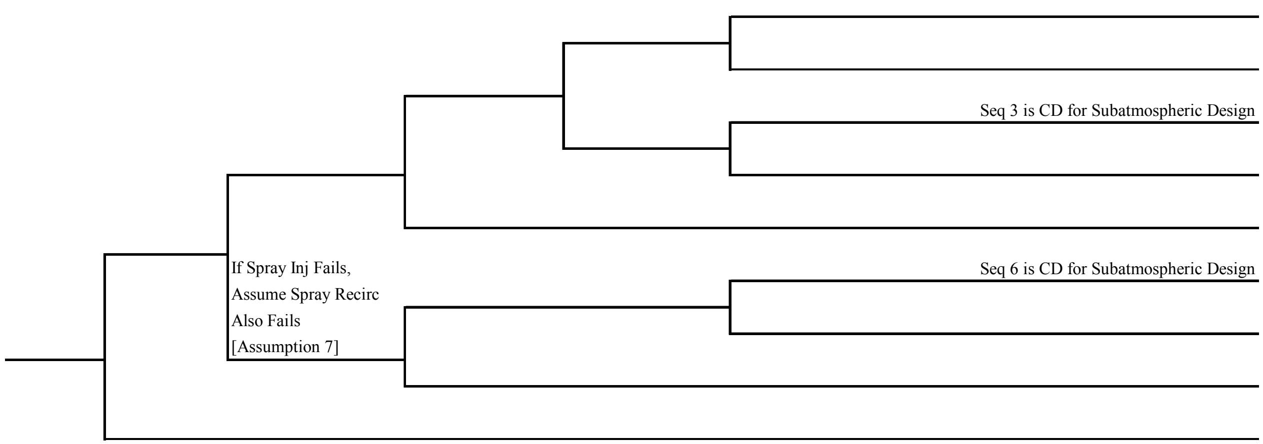
MLOCA-FUNC-NO-DEBRIS

Med LOCA 4 to 6 in	ECCS Inject. MLOCA	Containment Spray Injection	ECCS Recirc. MLOCA	Containment Spray Recirculation	Avoid Loss ECCS Recirc NPSH Margin Due to Debris	ECCS Recirc with Loss NPSH Margin	Recover from loss of ECCS Recirc due to Debris	#	END STATE NAMES
MLOCA	ECCS_INJ_M	SPRAY_INJ	ECCS_RECIRC_M	SPRAY_RECIRC	DEBRIS_OK_M	RECIRC_NPSHM_M	REC_DEBRIS_M		

Success Criteria: Reactor Trip * 1 Accumulator * 1/2 HHSI Train * 1/2 HHSR Trains piggybacked on LHSR [Assumptions 5, 9, 12]
For Subatmospheric Also Require: 1 Train Containment Spray Recirculation [Assumption 16]

Cooling not required from steam generators or feed & bleed; hole sufficiently large.
Also, hole sufficiently large such that depressurization to RHR/SDC possible w/o steam generators [Assumption 15]

Recovery Actions Are Plant/Sequence-Specific & Are Not Considered In The Sequences



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2	CD
3	OK/CD [Assump. 16]
4	CD
5	CD
6	OK/CD [Assump. 16]
7	CD
8	CD
9	CD

MLOCA-FUNC-DEBRIS

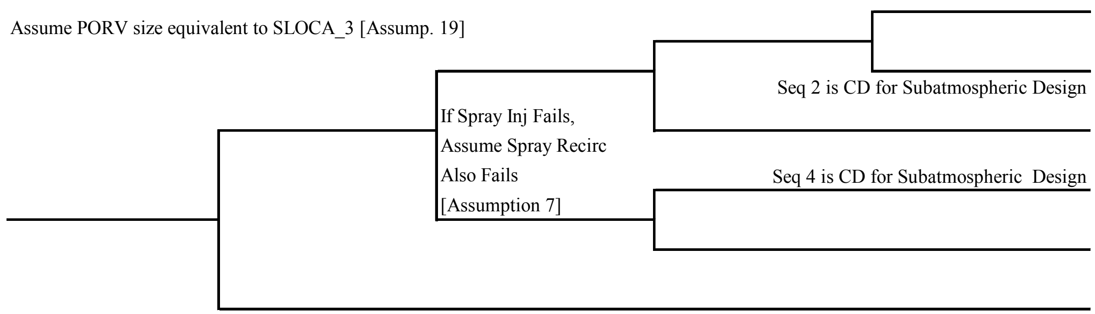
Transient/w Stuck Open PORV	ECCS Inject. SLOCA_3	Containment Spray Injection	ECCS Recirc. SLOCA_3	Containment Spray Recirculation	#	END STATE NAMES
TRANS_OPEN_PORV	ECCS_INJ_S3	SPRAY_INJ	ECCS_RECIRC_S3	SPRAY_RECIRC		

Open PORV is equivalent to SLOCA_3 except discharge is initially to pressurizer quench tank, then to ctmt after quench tank rupture disk fails

Success Criteria: Reactor Trip * 1/2 HHSI Train * 1/2 HHSR Trains piggybacked on LHSR [Assumptions 5, 12]
For Subatmospheric Also Require: 1 Train Containment Spray Recirculation [Assumption 16]

Cooling not required from steam generators or feed & bleed; hole sufficiently large.
Steam generators required for rapid depressurization to use RHR/SDC prior to ECCS switchover [Assump. 14]

Assume PORV size equivalent to SLOCA_3 [Assump. 19]



#	END STATE NAMES
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2	OK/CD [Assump. 16]
3	CD
4	OK/CD [Assump. 16]
5	CD
6	CD

OPENPORV-FUNC-NO-DEBRIS

Transient w/ Stuck Open PORV	ECCS Inject. SLOCA_3	Containment Spray Injection	ECCS Recirc. SLOCA_3	Containment Spray Recirculation	Avoid Loss ECCS Recirc NPSH Margin Due to Debris	ECCS Recirc with Loss NPSH Margin	Recover from loss of ECCS Recirc due to Debris	#	END STATE NAMES
Trans_OPEN_PORV	ECCS_INJ_S3	SPRAY_INJ	ECCS_RECIRC_S3	SPRAY_RECIRC	DEBRIS_OK_PO	RECIRC_NPSHM_PO	REC_DEBRIS_PO		

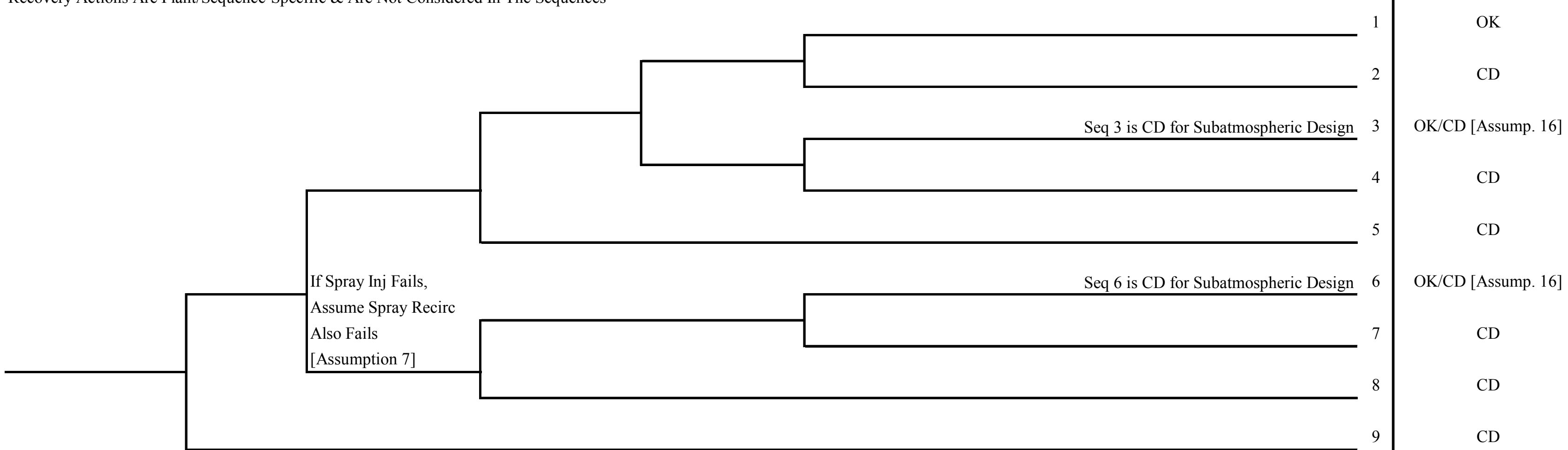
Open PORV is equivalent to SLOCA_3 except discharge is initially to pressurizer quench tank, then to ctmt after quench tank rupture disk fails

Success Criteria: Reactor Trip * 1/2 HHSI Train * 1/2 HHSR Trains piggybacked on LHSR [Assumptions 5, 12]
For Subatmospheric Also Require: 1 Train Containment Spray Recirculation [Assumption 16]

Cooling not required from steam generators or feed & bleed; hole sufficiently large.
Steam generators required for rapid depressurization to use RHR/SDC prior to ECCS switchover [Assump. 14]

Assume PORV size equivalent to SLOCA_3 [Assump. 19]

Recovery Actions Are Plant/Sequence-Specific & Are Not Considered In The Sequences



OPENPORV-DEBRIS

Small LOCA 1 to 2 in	ECCS Inject. SLOCA_2	Heat Removal w/ Steam Generator(s)	Open PORV(s) for Feed and Bleed	Fan Coolers Prevent Ctmt Spray Actuation	Containment Spray Injection	ECCS Recirc. SLOCA_2	Containment Spray Recirculation	#	END STATE NAMES
SLOCA_2	ECCS_INJ_S2	SG	FB	FAN_COOL	SPRAY_INJ	ECCS_RECIRC_S2	SPRAY_RECIRC		

Success Criteria: Reactor Trip * 1/2 HHSI Train * 1/2 HHSR Trains piggybacked on LHSR * heat removal using either 1 SG or feed & bleed [Assumptions 5, 12]
For Subatmospheric Also Require: 1 Train Containment Spray Recirculation [Assumption 16]

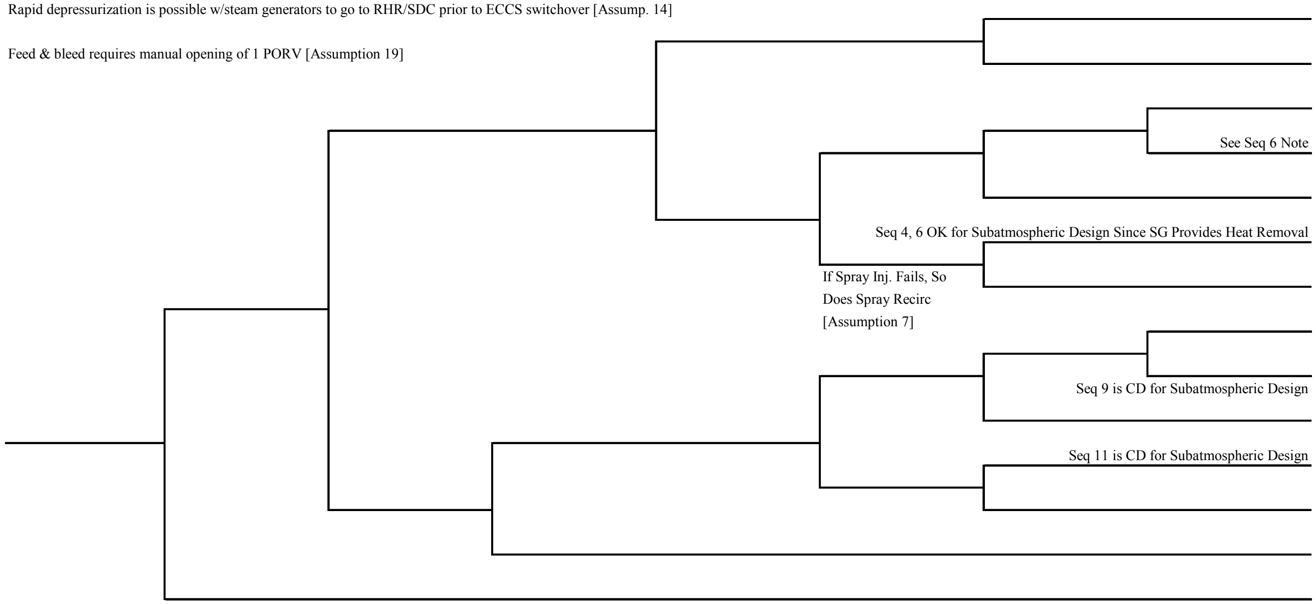
Use of feed & bleed discharges sufficient energy to containment (after quench tank rupture disk failure) such that spray actuation will occur even with operation of fan coolers [Assump. 13]

Fan coolers prevent spray actuation only for large-dry ctmts with: fan coolers operating after ECCS actuation and high pressure setpoint for spray actuation [Assumptions 17, 18]

Rapid depressurization is <u>not</u> possible w/feed & bleed (w/o steam generator heat removal) to go to RHR/SDC prior to ECCS switchover [Assump. 14]

Rapid depressurization is possible w/steam generators to go to RHR/SDC prior to ECCS switchover [Assump. 14]

Feed & bleed requires manual opening of 1 PORV [Assumption 19]



#	END STATE NAMES
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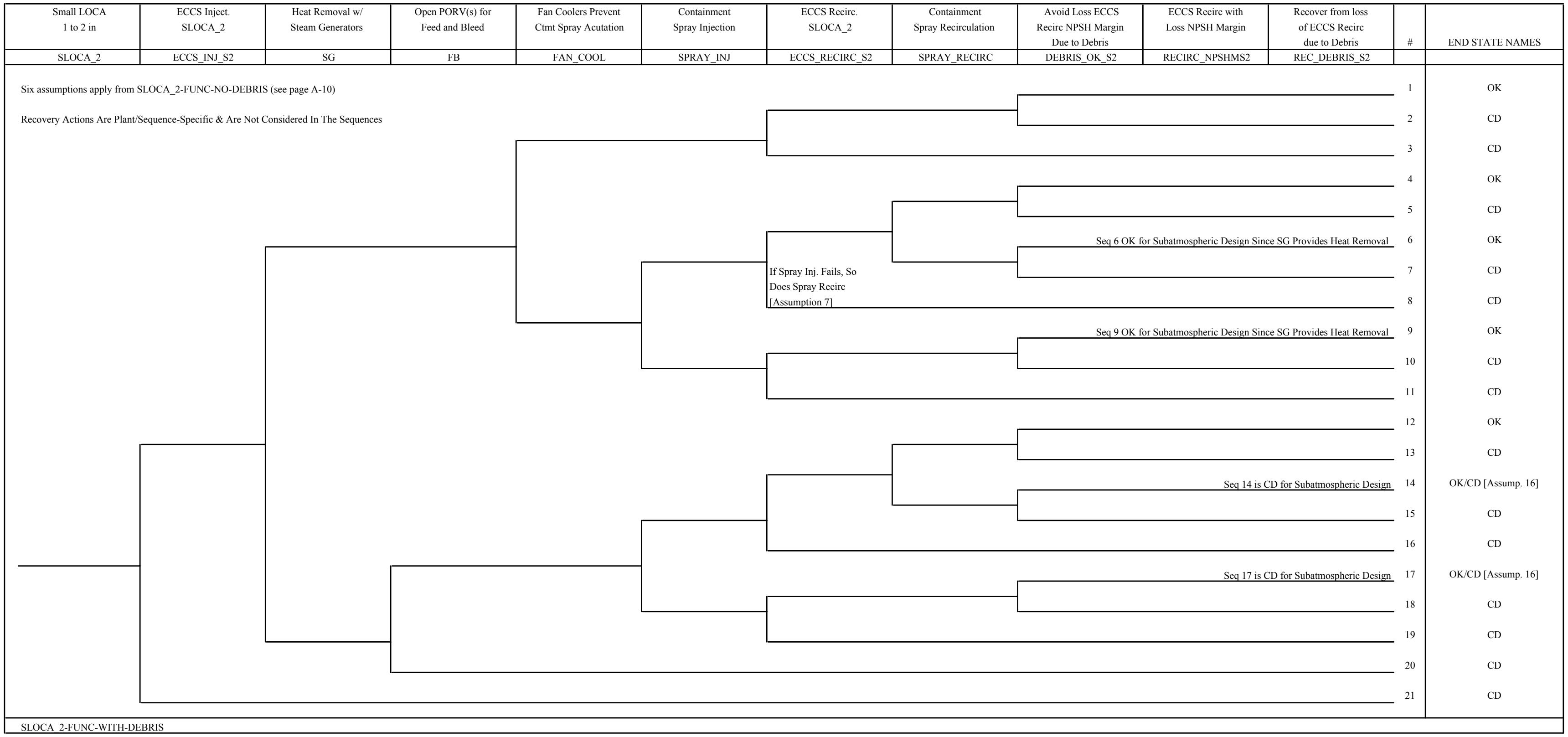
2	CD
3	OK
4	OK
5	CD
6	OK
7	CD
8	OK
9	OK/CD [Assump. 16]
10	CD
11	OK/CD [Assump. 16]
12	CD
13	CD
14	CD

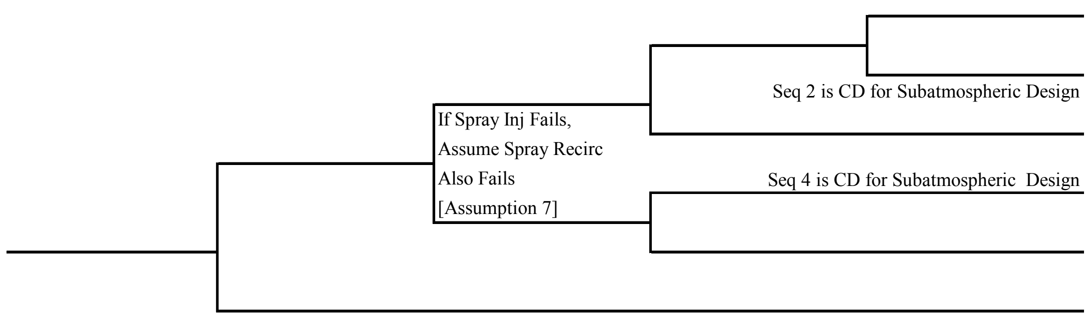
SLOCA_2-FUNC-NO-DEBRIS


Small LOCA 1 to 2 in
ECCS Inject. SLOCA_2
Heat Removal w/ Steam Generators
Open PORV(s) for Feed and Bleed
Fan Coolers Prevent Ctmt Spray Acutation
Containment Spray Injection
ECCS Recirc. SLOCA_2
Containment Spray Recirculation
Avoid Loss ECCS Recirc NPSH Margin Due to Debris
ECCS Recirc with Loss NPSH Margin
Recover from loss of ECCS Recirc due to Debris
#
END STATE NAMES
SLOCA_2
ECCS_INJ_S2
SG
FB
FAN_COOL
SPRAY_INJ
ECCS_RECIRC_S2
SPRAY_RECIRC
DEBRIS_OK_S2
RECIRC_NPSHMS2
REC_DEBRIS_S2
Six assumptions apply from SLOCA_2-FUNC-NO-DEBRIS (see page A-10)
Recovery Actions Are Plant/Sequence-Specific & Are Not Considered In The Sequences
If Spray Inj. Fails, So Does Spray Recirc [Assumption 7]
Seq 6 OK for Subatmospheric Design Since SG Provides Heat Removal
Seq 9 OK for Subatmospheric Design Since SG Provides Heat Removal
Seq 14 is CD for Subatmospheric Design
Seq 17 is CD for Subatmospheric Design
1 OK
2 CD
3 CD
4 OK
5 CD
6 OK
7 CD
8 CD
9 OK
10 CD
11 CD
12 OK
13 CD
14 OK/CD [Assump. 16]
15 CD
16 CD
17 OK/CD [Assump. 16]
18 CD
19 CD
20 CD
21 CD
SLOCA_2-FUNC-WITH-DEBRIS

Small LOCA 2 to 4 in	ECCS Inject. SLOCA_3	Containment Spray Injection	ECCS Recirc. SLOCA_3	Containment Spray Recirculation	#	END STATE NAMES
SLOCA_3	ECCS_INJ_S3	SPRAY_INJ	ECCS_RECIRC_S3	SPRAY_RECIRC		

Success Criteria: Reactor Trip * 1/2 HHSI Train * 1/2 HHSR Trains piggybacked on LHSR [Assumptions 5, 12]
For Subatmospheric Also Require: 1 Train Containment Spray Recirculation [Assumption 16]

Cooling not required from steam generators or feed & bleed; hole sufficiently large.
Steam generators required for rapid depressurization to use RHR/SDC prior to ECCS switchover [Assump. 14]



#	END STATE NAMES
1	OK
2	OK/CD [Assump. 16]
3	CD
4	OK/CD [Assump. 16]
5	CD
6	CD

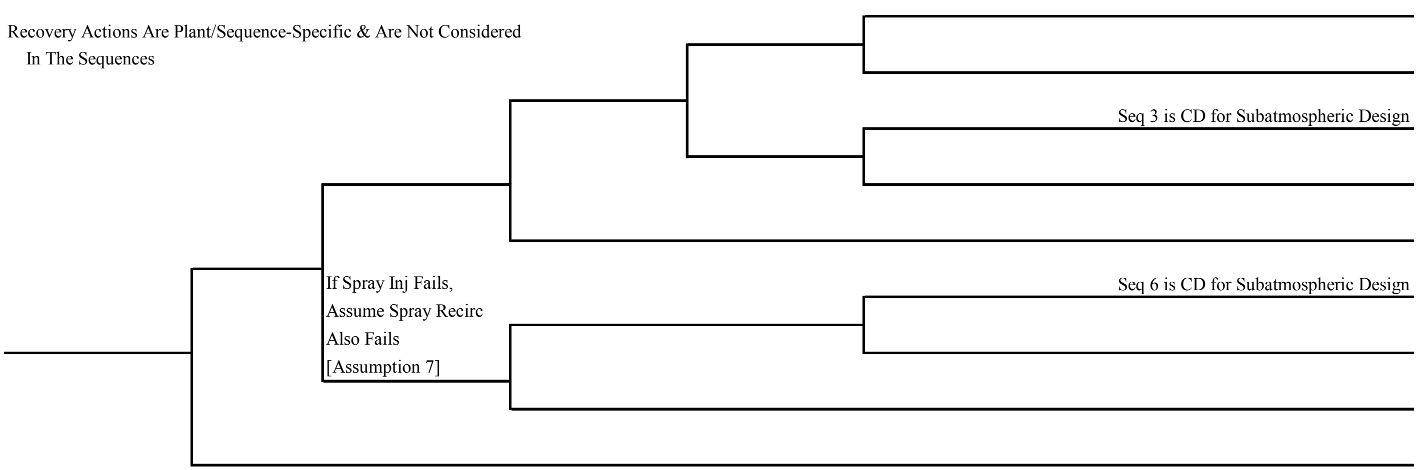
SLOCA_3-FUNC-NO-DEBRIS

Small LOCA 2 to 4 in	ECCS Inject. SLOCA_3	Containment Spray Injection	ECCS Recirc. SLOCA_3	Containment Spray Recirculation	Avoid Loss ECCS Recirc NPSH Margin Due to Debris	ECCS Recirc with Loss NPSH Margin	Recover from loss of ECCS Recirc due to Debris	#	END STATE NAMES
SLOCA_3	ECCS_INJ_S3	SPRAY_INJ	ECCS_RECIRC_S3	SPRAY_RECIRC	DEBRIS_OK_S3	RECIRC_NPSHMS3	REC_DEBRIS_S3		

Success Criteria: Reactor Trip * 1/2 HHSI Train * 1/2 HHSR Trains piggybacked on LHSR [Assumptions 5, 12]
For Subatmospheric Also Require: 1 Train Containment Spray Recirculation [Assumption 16]

Cooling not required from steam generators or feed & bleed; hole sufficiently large.
Steam generators required for rapid depressurization to use RHR/SDC prior to ECCS switchover [Assump. 14]

Recovery Actions Are Plant/Sequence-Specific & Are Not Considered
In The Sequences



#	END STATE NAMES
1	OK
2	CD
3	OK/CD [Assump. 16]
4	CD
5	CD
6	OK/CD [Assump. 16]
7	CD
8	CD
9	CD

SLOCA_3-WITH-DEBRIS

APPENDIX B

B.1 Introduction

This appendix provides additional details related to the quantification of the event trees and other supporting material, including major assumptions. This appendix also describes important factors that affect the likelihood of sump unavailability.

As described in the main body of the report, five specific types of accident conditions were addressed. These accident conditions are summarized in Table B-1.

These initiating events were analyzed by using the event trees shown in Attachment A. Three general parametric cases were evaluated for each event-tree model. These parametric cases are based on typical designs for the following three types of containment: large dry, ice condenser, and subatmospheric.

Table B-1 Summary of Analyzed Accident Conditions

Initiator	Initiator Subcategory	Description
Small LOCA (SLOCA)	SLOCA-1	This is a small LOCA with a break of equivalent diameter of less than about 1 in. Normal makeup can mitigate this size of break. This break category was not analyzed further.
	SLOCA-2	This is a small LOCA with a break size of equivalent diameter between about 1 and 2 in. For this size break, high-head emergency coolant injection is required. The break size is sufficiently small such that energy out the break cannot match decay heat and heat removal from either a steam generator or feed and bleed is required. If heat removal with a steam generator is available, it may be possible to depressurize the primary and use RHR in the SDC mode before the ECCS switches from injection to recirculation. If steam generator cooling is not available and feed and bleed is used for core cooling instead, it is assumed not possible to depressurize and use RHR/SDC before switchover of ECCS from injection to recirculation. For large dry containment designs having fan coolers that remain operational after an ECCS actuation signal and for which the actuation set point for spray injection is sufficiently high, it is assumed that operation of the fan coolers will prevent actuation of the containment sprays.
	SLOCA-3	This is a small LOCA with a break size of equivalent diameter between about 2 and 4 in. For this size break, high-head emergency coolant injection is required. The break size is sufficiently large such that energy out the break can match decay. If heat removal with a steam generator is available, it may be possible to depressurize the primary and use RHR in the SDC mode before the ECCS switches from injection to recirculation. If heat removal with a steam generator is not available, it is assumed that it is not possible to depressurize and use RHR/SDC before switchover of ECCS from injection to recirculation. It is assumed that operation of fan coolers, if available, will not prevent actuation of containment spray.
Medium LOCA (MLOCA)	None	This is a LOCA with a break size of equivalent diameter between about 4 and 6 in. This break is assumed to behave exactly as a SLOCA-3 in terms of ECCS requirements with an additional requirement for accumulator injection. (For some plants, the MLOCA may have ECCS injection requirements more like a LLOCA than like a SLOCA-3.) Because of the size of the break, it is assumed that it is possible to depressurize and use RHR/SDC before switchover of ECCS from injection to recirculation. It is assumed that operation of fan coolers, if available, will not prevent actuation of containment spray.
Large LOCA (LLOCA)	None	The LLOCA represents a break size of equivalent diameter of about 6 in. This break size requires low-head ECCS core flow and accumulator flow.
Transient with Stuck Open Primary Relief Valve (TRAN-PORV)	None	Transient with Stuck Open Primary Relief Valve (TRAN-PORV): Functionally this initiator is identical to the SLOCA-3 as a stuck open PORV is equivalent to a LOCA of about 2 in. in size. However, this initiator was treated separately because its debris effects and recovery potential may be more favorable than for the SLOCA-3. Specifically, for the stuck-open PORV, the discharge is initially to the pressurizer quench tank, and release from that tank into containment only occurs after the pressure of the rupture disk on the quench tank is reached. Also, a possible action to recover from loss of ECCS recirculation is to depressurize and use RHR/SDC, and for this accident, the break is sufficiently high in elevation that it does not require continued makeup while on RHR/SDC. In contrast, the SLOCA-3 break may be in a location where continued makeup is required while on RHR/SDC.
Loss of all Feedwater (TRAN-LOFW)	None	Functionally, this event tree is almost identical to the SLOCA-3 initiator as feed and bleed requires use of a PORV that has a size equivalent to a LOCA of about 2 in.

Table B-2 lists important factors that affect sump availability.

An accurate calculation of conditional probability for avoiding loss of NPSH margin is plant-specific. However, certain common factors will apply to every plant, specifically the following.

1. Time to switchover from injection to recirculation (SWITCH)
2. Spray flow during Injection (SPRAYINJ)
3. Flow rate from ECCS sump in recirculation (SUMPFLOW)
4. Probability that sump is lost because of a combination of (a) problematic debris and (b) the sump failure threshold for debris loading (PSUMPLOST)

Numerical estimates for the first three factors are provided in the following subsections. Numerical estimates of the fourth factor (sump failure) are provided in Attachment C. Note that although factors (1) through (3) apply to all sequences, these factors are sequence-specific. Factor (4) applies to all sequences but is not sequence-specific.

Table B-2 Important Factors That Affect Sump Availability

Factor	Applicable Accident Types	Debris Phenomena
Number of ECCS trains operating during Injection: 1, 2 (0 results in core melt)	All	Less settling of debris for earlier time of switchover to recirculation
Number of spray trains operating during Injection: none, 1, 2	All	Less settling of debris for earlier time of switchover to recirculation Sprays affect transport of debris
Number of ECCS trains operating during recirculation: 1, 2 (0 results in core melt)	All	Head loss increases with flow from sump
Number of spray trains operating during recirculation: none, 1, 2 (none results in core melt for subatmospheric design, Assumption #16)	All	Head loss increases with flow from sump
Type of debris	All	Some types of debris are worse that other types in terms of affecting the ECCS sump
Sump design characteristics	All	Some types of sump designs are more susceptible to debris effects than others Some plants have more than one ECCS sump and may have separate sumps for core cooling and spray pumps
Fan coolers cannot prevent spray actuation	LLOCA, MLOCA, SLOCA-3	Time of switchover to recirculation reduced because containment spray actuation occurs; less settling of debris
Fan coolers can prevent spray actuation if feed and bleed is not used	SLOCA-2	If feed and bleed is not used, the time from switchover to recirculation is increased because containment spray actuation is prevented by fan coolers; more settling of debris Note: this attribute applies to plants with large dry containments, fan coolers, and a relatively high spray actuation set point
Use of feed and bleed (1, 2 PORVs)	SLOCA-2, TRAN-LOFW	Less settling of debris for earlier time of switchover to recirculation Assume use of PORVs does not generate additional debris (flow to quench tank, rupture disk opens after quench tank filled, discharge of quench tank assumed to be away from significant source of insulation)

To generate numerical estimates for switchover time (SWITCH), injection spray flow (SPRAYINJ), and sump recirculation flow (SUMFLOW), certain assumptions were made with regard to ECCS flow rates and RWST capacity.

- Except for large LOCAs, the RCS does not depressurize to the low-head ECCS set point.
- ECCS core injection consists of two trains.
- For large LOCAs, ECCS core injection flow per train is 3000 gal./min (low-head pumps).
- For the medium LOCA and SLOCA-3, core injection flow per train is 1200 gal./min (runout flow for high-head pumps).
- For SLOCA-2, core injection flow per train is 600 gal./min with no feed and bleed; if feed and bleed is used, core injection flow per train is 1200 gal./min (runout flow for high-head pumps)
- For transient with stuck-open PORV and loss of all feedwater, core injection flow per train is 1200 gal./min (runout flow for high-head pumps)
- Containment spray consists of two trains; flow per train is 6000 gal./min
- The useful quantity of RWST inventory is as follows: 270,000 gal. (large dry); 180,000 gal. (ice condenser); and 300,000 gal. (subatmospheric)

Estimates of initiating-event frequencies and system failure probabilities also were generated to support the event-tree analysis. These items of supporting data also are described in the following subsections.

The system failure probabilities are based on typical unavailability data for plant systems. To simplify the modeling process, mitigating system successes and failures were assumed to be independent, except for dependence between the containment spray injection and recirculation modes. The containment spray injection and recirculation modes were assumed to be dependent such that a failure of containment spray injection automatically results in a failure of containment spray recirculation. To correctly perform an actual plant-specific analysis, it would be necessary to account for common failures across systems by a Boolean linking of the logic models for all systems. This Boolean linking would require detailed system fault trees, an activity beyond the scope of this project.

B.2 Large LOCA (LLOCA) Accident

Table B-3 lists the initiating event and system unavailability data assumed in the LLOCA event-tree quantification.

Table B-4 provides numerical estimates for switchover time (SWITCH), injection spray flow (SPRAYINJ), and sump recirculation flow (SUMFLOW) for the Large LOCA.

Table B-3 Initiating Event and System Unavailability Data for LLOCA

Item	Quantification	Event Tree Heading	Notes/Reference
Initiating Event Frequency			
Traditional PRA	5E-04/yr	LLOCA	"Evaluation of Severe Accident Risks: Zion, Unit 1," NUREG/CR-4551, Vol. 7, Rev, 1, July 1989.
Leak-Before-Break	3.6E-06/yr	LLOCA	"Rates of Initiating Events at U. S. Nuclear Power Plants: 1987-1995," NUREG/CR-5750, February 1999. See Table 3-1 and p. J-11 of above reference
System Unavailability Data			
Failure of ECCS Injection (Both Trains)	1E-03	ECCS-INJ-L	
Failure of Containment Spray Injection (Both Trains)	1E-03	SPRAY-INJ	
Failure of ECCS Recirculation (Both Trains)	6E-03	ECCS-RECIRC-L	Includes failure to switch to hot-leg recirculation (this action is required in **Comanche Peak IPE** during 24-h PRA mitigation period to prevent boron precipitation)
Failure of Containment Spray Recirculation (Both Trains)	1E-03	SPRAY-RECIRC	

Table B-4 Flow Parameters for Large LOCA (LLOCA)				
System Status	**Flow Rate (gpm)**	**Time to Switchover (minutes)**	**Spray Injection Flow (gpm)**	**Sump Flow (gpm)**
Large Dry Containment				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	18,000	15		
One Train ECCS Injection and One Train Containment Spray Injection	9,000	30		
Both Trains ECCS Injection and No Containment Spray	6,000	45		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation				18,000
One Train ECCS Recirculation and One Train Containment Spray Recirculation				9,000
Both Trains ECCS Recirculation and No Containment Spray				6,000
Ice Condenser				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	18,000	10		
One Train ECCS Injection and One Train Containment Spray Injection	9,000	20		
Both Trains ECCS Injection and No Containment Spray	6,000	30		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation				18,000
One Train ECCS Recirculation and One Train Containment Spray Recirculation				9,000
Both Trains ECCS Recirculation and No Containment Spray				6,000
Subatmospheric				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	18,000	17		
One Train ECCS Injection and One Train Containment Spray Injection	9,000	33		
Both Trains ECCS Injection and No Containment Spray	6,000	50		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation (see note below)				18,000
One Train ECCS Recirculation and One Train Containment Spray Recirculation (see note below)				9,000
Both Trains ECCS Recirculation and No Containment Spray (see note below)				6,000
Note: For the subatmospheric containment, the inside and outside recirculation pumps are designed to start about 2 and 5 min, respectively, after ECCS actuation; these pumps only draw coolant from the sump				

B.3 Medium LOCA (MLOCA) Accident
Table B-5 lists the initiating event and system unavailability data assumed in the MLOCA event-tree quantification.

Table B-6 provides numerical estimates for switchover time (SWITCH), injection spray flow (SPRAYINJ), and sump recirculation flow (SUMFLOW) for the medium LOCA.

B.4 SLOCA-3 Accident
Table B-7 lists the initiating event and system unavailability data assumed in the SLOCA-3 event tree quantification.

Table B-8 provides numerical estimates for switchover time (SWITCH), injection spray flow (SPRAYINJ), and sump recirculation flow (SUMFLOW) for the SLOCA-3.

B.5 SLOCA-2 Accident

Table B-9 lists the initiating event and system unavailability data assumed in the SLOCA-2 event-tree quantification.

Table B-10 provides numerical estimates for switchover time (SWITCH), injection spray flow (SPRAYINJ), and sump recirculation flow (SUMFLOW) for the SLOCA-2.

B.6 Transient with Stuck-Open PORV Accident

For the Transient with Stuck-Open PORV accident, the system failure probabilities and deterministic parameters (flow rates, etc.) are the same as for SLOCA-3. No attempt was made to adjust deterministic parameters to account for the fact that the PORV initially discharges into a quench tank and coolant will enter containment only after the quench tank rupture disk is opened. A more refined model would account for a corresponding delay in containment spray actuation and the effects of this delay on flow and switchover estimates.

Table B-11 lists the initiating event and system unavailability data assumed in the Transient with Stuck-Open PORV event-tree quantification.

Table B-5 Initiating Event and System Unavailability Data for MLOCA

Item	Quantification	Event-Tree Heading	Notes/Reference
Initiating Event Frequency			
Traditional PRA	1E-03/yr	MLOCA	"Evaluation of Severe Accident Risks: Zion, Unit 1," NUREG/CR-4551, Vol. 7, Rev, 1, July 1989.
Leak-Before-Break	1.9E-05/yr	MLOCA	"Rates of Initiating Events at U. S. Nuclear Power Plants: 1987-1995," NUREG/CR-5750, February 1999. Medium LOCA frequency data for LBB are provided on p. J-13 of the above reference; the total suggested medium LOCA frequency in this reference is 3.0E-05/yr based on combining failure data for 2.5-in. piping (1.1E-05/yr) and 6-in. piping (is cited as and 1.9E-05/yr); however, the definition of a medium LOCA in our analysis is a 4 to 6-in. break; thus, 1.9E-05/yr was selected as the appropriate initiator frequency for our analysis
System Unavailability Data			
Failure of ECCS Injection (Both Trains)	1E-03	ECCS-INJ-M	
Failure of Containment Spray Injection (Both Trains)	1E-03	SPRAY-INJ	
Failure of ECCS Recirculation (Both Trains)	1E-03	ECCS-RECIRC-M	
Failure of Containment Spray Recirculation (Both Trains)	1E-03	SPRAY-RECIRC	

Table B-6 Flow Parameters for MLOCA				
System Status	**Flow Rate (gal./min)**	**Time to Switchover (minutes)**	**Spray Injection Flow (gal./min)**	**Sump Flow (gal./min)**
Large Dry Containment				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	14,400	19		
One Train ECCS Injection and One Train Containment Spray Injection	7,200	38		
Both Trains ECCS Injection and No Containment Spray	2,400	113		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation				14,400
One Train ECCS Recirculation and One Train Containment Spray Recirculation				7,200
Both Trains ECCS Recirculation and No Containment Spray				2,400
Ice Condenser				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	14,400	13		
One Train ECCS Injection and One Train Containment Spray Injection	7,200	25		
Both Trains ECCS Injection and No Containment Spray	2,400	75		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation				14,400
One Train ECCS Recirculation and One Train Containment Spray Recirculation				7,200
Both Trains ECCS Recirculation and No Containment Spray				2,400
Subatmospheric				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	14,400	21		
One Train ECCS Injection and One Train Containment Spray Injection	7,200	42		
Both Trains ECCS Injection and No Containment Spray	2,400	125		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation (see note below)				14,400
One Train ECCS Recirculation and One Train Containment Spray Recirculation (see note below)				7,200
Both Trains ECCS Recirculation and No Containment Spray (see note below)				2,400
Note: For the subatmospheric containment, the inside and outside recirculation pumps are designed to start about 2 and 5 min, respectively, after ECCS actuation; these pumps only draw coolant from the sump				

Table B-7 Initiating Event and System Unavailability Data for SLOCA-3			
Item	**Quantification**	**Event Tree Heading**	**Notes/Reference**
Initiating Event Frequency			
Traditional PRA	5E-04/yr	SLOCA-3	Divided by a factor of two the small LOCA frequency of 1E-03/yr used in "Evaluation of Severe Accident Risks: Zion, Unit 1," NUREG/CR-4551, Vol. 7, Rev, 1, July 1989. This frequency was divided by a factor of 2 to apportion the initiator across the two sizes of small LOCA analyzed in our analysis, specifically SLOCA-3 (2–4 in.) and SLOCA-2 (1–2 in.) Frequency only intended to include pipe breaks; does not include reactor coolant pump (RCP) seal LOCA (RCP seal LOCA not expected to generate significant amount of debris)
Leak-Before-Break	1.1E-05/yr	SLOCA-3	Data gathered from "Rates of Initiating Events at U. S. Nuclear Power Plants: 1987-1995," NUREG/CR-5750, February 1999; page J-13 of the above reference cites failure data for 2.5-in. piping as 1.1E-05/yr; this value was used to represent the frequency of SLOCA-3, which is a 2- to 4-in. break The small LOCA frequency cited in NUREG/CR-5750 references to pipe breaks in the ½- to 2-in. range (see p. A-4), and thus, the NUREG/CR-5750 small LOCA frequency data were judged to be <u>not</u> applicable to the SLOCA-3 in our analysis Frequency only intended to include pipe breaks; does not include RCP seal LOCA (RCP seal LOCA not expected to generate significant amount of debris)
System Unavailability Data			
Failure of ECCS Injection (Both Trains)	1E-03	ECCS-INJ-S3	
Failure of Containment Spray Injection (Both Trains)	1E-03	SPRAY-INJ	
Failure of ECCS Recirculation (Both Trains)	1E-03	ECCS-RECIRC-S3	
Failure of Containment Spray Recirculation (Both Trains)	1E-03	SPRAY-RECIRC	

Table B-8 Flow Parameters for SLOCA-3				
System Status	Flow Rate (gal./min)	Time to Switchover (minutes)	Spray Injection Flow (gal./min)	Sump Flow (gal./min)
Large Dry Containment				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	14,400	19		
One Train ECCS Injection and One Train Containment Spray Injection	7,200	38		
Both Trains ECCS Injection and No Containment Spray	2,400	113		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation				14,400
One Train ECCS Recirculation and One Train Containment Spray Recirculation				7,200
Both Trains ECCS Recirculation and No Containment Spray				2,400
Ice Condenser				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	14,400	13		
One Train ECCS Injection and One Train Containment Spray Injection	7,200	25		
Both Trains ECCS Injection and No Containment Spray	2,400	75		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation				14,400
One Train ECCS Recirculation and One Train Containment Spray Recirculation				7,200
Both Trains ECCS Recirculation and No Containment Spray				2,400
Subatmospheric				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	14,400	21		
One Train ECCS Injection and One Train Containment Spray Injection	7,200	42		
Both Trains ECCS Injection and No Containment Spray	2,400	125		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation (see note below)				14,400
One Train ECCS Recirculation and One Train Containment Spray Recirculation (see note below)				7,200
Both Trains ECCS Recirculation and No Containment Spray (see note below)				2,400
Note: For the subatmospheric containment, the inside and outside recirculation pumps are designed to start about 2 and 5 min, respectively, after ECCS actuation; these pumps only draw coolant from the sump				

Table B-9 Initiating Event and System Unavailability Data for SLOCA-2			
Item	**Quantification**	**Event Tree Heading**	**Notes/Reference**
Initiating Event Frequency			
Traditional PRA	5E-04/yr	SLOCA-2	Divided by a factor of 2, the small LOCA frequency of 1E-03/yr used in "Evaluation of Severe Accident Risks: Zion, Unit 1," NUREG/CR-4551, Vol. 7, Rev, 1, July 1989. The NUREG/CR-4551frequency was divided by a factor of 2 to apportion the initiator across the two sizes of small LOCA analyzed in our analysis, specifically SLOCA-3 (2 to 4 in.) and SLOCA-2 (1 to 2 in.) Frequency only intended to include pipe breaks; does not include RCP seal LOCA (RCP seal LOCA not expected to generate significant amount of debris)
Leak-Before-Break	2.3E-04/yr	SLOCA-2	Data gathered from "Rates of Initiating Events at U. S. Nuclear Power Plants: 1987-1995," NUREG/CR-5750, February 1999; p. J-16 of the above reference cites failure data for a small LOCA as 2.3E-04/yr; a small LOCA as used in NUREG/CR-5750 represents a pipe break in the ½- to 2-in. range (see p. A-4) The SLOCA-2 category used in our analysis is a 1- to 2-in. pipe break; thus, our use of the NUREG/CR-5750 small LOCA frequency is conservative as it also includes pipe breaks in the ½- to 1-in. range; no attempt was made to adjust the NUREG/CR-5750 data to account for this overestimate Frequency only intended to include pipe breaks; does not include RCP seal LOCA (RCP seal LOCA not expected to generate significant amount of debris)
System Unavailability Data			
Failure of ECCS Injection (Both Trains)	1E-03	ECCS-INJ-S2	
Failure of Containment Spray Injection (Both Trains)	1E-03	SPRAY-INJ	
Failure of ECCS Recirculation (Both Trains)	1E-03	ECCS-RECIRC-S2	
Failure of Containment Spray Recirculation (Both Trains)	1E-03	SPRAY-RECIRC	
Failure of Heat Removal with Steam Generators	1E-03	SG	
Failure of Feed and Bleed (Fail to Open PORV(s) for Feed and Bleed)	2E-03	FB	This event only accounts for failure of operators to open PORV(s) to support feed and bleed; failure of ECCS pump flow portion of feed and bleed accounted for in event ECCS-INJ-S2
Failure of Fan Coolers	1E-02, given fan coolers available and high spray actuation set point. Estimate 30% of plants have fan coolers available and high spray actuation set point.	FAN-COOL	Fan coolers can prevent containment spray actuation for large dry containments with fan coolers operational after ECCS actuation and high-pressure set point for spray actuation

Table B-10 Flow Parameters for SLOCA-2				
System Status	**Flow Rate (gal./min)**	**Time to Switchover (minutes)**	**Spray Injection Flow (gal./min)**	**Sump Flow (gal./min)**
Large Dry Containment				
No Feed and Bleed				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	13,200	20		
One Train ECCS Injection and One Train Containment Spray Injection	6,600	41		
Both Trains ECCS Injection and No Containment Spray	1,200	225		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation				13,200
One Train ECCS Recirculation and One Train Containment Spray Recirculation				6,600
Both Trains ECCS Recirculation and No Containment Spray				1,200
Feed and Bleed				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	14,400	19		
One Train ECCS Injection and One Train Containment Spray Injection	7,200	38		
Both Trains ECCS Injection and No Containment Spray	2,400	113		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation				14,400
One Train ECCS Recirculation and One Train Containment Spray Recirculation				7,200
Both Trains ECCS Recirculation and No Containment Spray				2,400
Ice Condenser				
No Feed and Bleed				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	13,200	14		
One Train ECCS Injection and One Train Containment Spray Injection	6,600	27		
Both Trains ECCS Injection and No Containment Spray	1,200	150		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation				13,200
One Train ECCS Recirculation and One Train Containment Spray Recirculation				6,600
Both Trains ECCS Recirculation and No Containment Spray				1,200
Feed and Bleed				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	14,400	13		

Table B-10 Flow Parameters for SLOCA-2				
System Status	**Flow Rate (gal./min)**	**Time to Switchover (minutes)**	**Spray Injection Flow (gal./min)**	**Sump Flow (gal./min)**
One Train ECCS Injection and One Train Containment Spray Injection	7,200	25		
Both Trains ECCS Injection and No Containment Spray	2,400	75		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation				14,400
One Train ECCS Recirculation and One Train Containment Spray Recirculation				7,200
Both Trains ECCS Recirculation and No Containment Spray				2,400
Subatmospheric				
No Feed and Bleed				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	13,200	23		
One Train ECCS Injection and One Train Containment Spray Injection	6,600	45		
Both Trains ECCS Injection and No Containment Spray	1,200	250		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation (see note below)				13,200
One Train ECCS Recirculation and One Train Containment Spray Recirculation (see note below)				6,600
Both Trains ECCS Recirculation and No Containment Spray (see note below)				1,200
Feed and Bleed				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	14,400	21		
One Train ECCS Injection and One Train Containment Spray Injection	7,200	42		
Both Trains ECCS Injection and No Containment Spray	2,400	125		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation (see note below)				14,400
One Train ECCS Recirculation and One Train Containment Spray Recirculation (see note below)				7,200
Both Trains ECCS Recirculation and No Containment Spray (see note below)				2,400
Note: For the subatmospheric containment, the inside and outside recirculation pumps are designed to start about 2 and 5 min, respectively, after ECCS actuation; these pumps only draw coolant from the sump				

Table B-11 Initiating Event and System Unavailability Data for Transient with Stuck Open PORV			
Item	**Quantification**	**Event-Tree Heading**	**Notes/Reference**
Initiating-Event Frequency			
Typical PRA value	1E-03/yr	TRANS-OPEN-PORV	Data gathered from "Rates of Initiating Events at U. S. Nuclear Power Plants: 1987-1995," NUREG/CR-5750, February 1999; Table 3-1, p. 11 cites a frequency of 1.0E-03/yr for a stuck-open PORV Leak-before-break considerations do not apply to stuck-open PORV
System Unavailability Data			
Failure of ECCS Injection (Both Trains)	1E-03	ECCS-INJ-S3	
Failure of Containment Spray Injection (Both Trains)	1E-03	SPRAY-INJ	
Failure of ECCS Recirculation (Both Trains)	1E-03	ECCS-RECIRC-S3	
Failure of Containment Spray Recirculation (Both Trains)	1E-03	SPRAY-RECIRC	

Table B-12 provides numerical estimates for switchover time (SWITCH), injection spray flow (SPRAYINJ), and sump recirculation flow (SUMFLOW) for the Transient with Stuck Open PORV.

B.7 LOFW Accident

For the LOFW accident, the system failure probabilities and deterministic parameters (flow rates, etc.) are the same as for SLOCA-3. No attempt was made to adjust deterministic parameters to account for the fact that the PORV (used for feed-and-bleed cooling) initially discharges into a quench tank, and coolant will enter containment only after the quench tank rupture disk is opened. A more refined model would account for a corresponding delay in containment spray actuation and the effects of this delay on flow and switchover estimates.

Table B-13 lists the initiating event and system unavailability data assumed in the LOFW event-tree quantification.

Table B-14 provides numerical estimates for switchover time (SWITCH), injection spray flow (SPRAYINJ), and sump recirculation flow (SUMFLOW) for the Loss of Feedwater.

B.8 Averaging of Plant Characteristics

CDF estimates generated from this analysis are intended to represent averages over all PWRs with respect to design characteristics. This averaging has been done by weighting design-specific aspects in the model by the relative fraction of plants in each of three containment design categories (large dry, ice condenser, and subatmospheric). Over a total population of 69 PWR reactor units, 53 have large dry containments, 9 have ice condenser containments, and the remaining 7 have subatmospheric containments. Thus, the overall CDF results were derived by apportioning results from the individual containment design categories as follows: 0.77 for large dry containment plants based on 53/69 units with large dry containments, 0.13 for ice condenser containment plants based on 9/69 units with ice condenser containments, and 0.10 for subatmospheric containment plants based on 7/69 units with atmospheric containments.

Table B-12 Flow Parameters for Transient with Stuck-Open PORV				
System Status	Flow Rate (gal./min)	Time to Switchover (minutes)	Spray Injection Flow (gal./min)	Sump Flow (gal./min)
Large Dry Containment				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	14,400	19		
One Train ECCS Injection and One Train Containment Spray Injection	7,200	38		
Both Trains ECCS Injection and No Containment Spray	2,400	113		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation				14,400
One Train ECCS Recirculation and One Train Containment Spray Recirculation				7,200
Both Trains ECCS Recirculation and No Containment Spray				2,400
Ice Condenser				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	14,400	13		
One Train ECCS Injection and One Train Containment Spray Injection	7,200	25		
Both Trains ECCS Injection and No Containment Spray	2,400	75		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation				14,400
One Train ECCS Recirculation and One Train Containment Spray Recirculation				7,200
Both Trains ECCS Recirculation and No Containment Spray				2,400
Subatmospheric				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	14,400	21		
One Train ECCS Injection and One Train Containment Spray Injection	7,200	42		
Both Trains ECCS Injection and No Containment Spray	2,400	125		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation (see note below)				14,400
One Train ECCS Recirculation and One Train Containment Spray Recirculation (see note below)				7,200
Both Trains ECCS Recirculation and No Containment Spray (see note below)				2,400
Note: For the subatmospheric containment, the inside and outside recirculation pumps are designed to start about 2 and 5 min, respectively, after ECCS actuation; these pumps only draw coolant from the sump				

Table B-13 Initiating-Event and System Unavailability Data for Loss of All Feedwater			
Item	**Quantification**	**Event Tree Heading**	**Notes/Reference**
Initiating Event Frequency			
Loss of all feedwater	1E-04/yr	LOFW	Estimate initiating-event frequency to be ~1E-04/yr by combining generic loss-of-main-feedwater initiating-event frequency of 8.5E-02/yr and AFW system failure probability of 1E-03 (i.e., (8.5E-02/yr)*(1E-03) = ~1E-04/yr) Loss-of-main-feedwater frequency cited as 8.5E-02/yr in Table 3-1, p. 11, “Rates of Initiating Events at U. S. Nuclear Power Plants: 1987-1995,” NUREG/CR-5750, February 1999; Table 3-1, p. 11
System Unavailability Data			
Failure of ECCS Injection (Both Trains)	1E-03	ECCS-INJ-S3	
Failure of Containment Spray Injection (Both Trains)	1E-03	SPRAY-INJ	
Failure of ECCS Recirculation (Both Trains)	1E-03	ECCS-RECIRC-S3	
Failure of Containment Spray Recirculation (Both Trains)	1E-03	SPRAY-RECIRC	
Failure of Feed and Bleed [Fail to Open PORV(s) for Feed and Bleed]	2E-03	FB	This event only accounts for failure of operators to open PORV(s) to support feed and bleed; failure of ECCS pump flow portion of feed and bleed accounted for in event ECCS-INJ-S3
Failure of Fan Coolers	1E-02, given fan coolers available and high spray actuation set point. Estimate 30% of plants have fan coolers available and high spray actuation set point.	FAN-COOL	Fan coolers can prevent containment spray actuation for large dry containments with fan coolers operational after ECCS actuation and high-pressure set point for spray actuation

Table B-14 Flow Parameters for Loss of All Feedwater				
System Status	**Flow Rate (gal./min)**	**Time to Switchover (min)**	**Spray Injection Flow (gal./min)**	**Sump Flow (gal./min)**
Large Dry Containment				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	14,400	19		
One Train ECCS Injection and One Train Containment Spray Injection	7,200	38		
Both Trains ECCS Injection and No Containment Spray	2,400	113		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation				14,400
One Train ECCS Recirculation and One Train Containment Spray Recirculation				7,200
Both Trains ECCS Recirculation and No Containment Spray				2,400
Ice Condenser				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	14,400	13		
One Train ECCS Injection and One Train Containment Spray Injection	7,200	25		
Both Trains ECCS Injection and No Containment Spray	2,400	75		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation				14,400
One Train ECCS Recirculation and One Train Containment Spray Recirculation				7,200
Both Trains ECCS Recirculation and No Containment Spray				2,400
Subatmospheric				
Both Trains ECCS Injection and Both Trains Containment Spray Injection	14,400	21		
One Train ECCS Injection and One Train Containment Spray Injection	7,200	42		
Both Trains ECCS Injection and No Containment Spray	2,400	125		
No Containment Spray Injection			0	
One Train Containment Spray Injection			6,000	
Both Trains Containment Spray Injection			12,000	
Both Trains ECCS Recirculation and Both Trains Containment Spray Recirculation (see note below)				14,400
One Train ECCS Recirculation and One Train Containment Spray Recirculation (see note below)				7,200
Both Trains ECCS Recirculation and No Containment Spray (see note below)				2,400
Note: For the subatmospheric containment, the inside and outside recirculation pumps are designed to start about 2 and 5 min, respectively, after ECCS actuation; these pumps only draw coolant from the sump				

B.9 Assumptions

Various assumptions used in the event-tree models are listed below. Many of these assumptions are specifically referenced on the event trees.

1. Assume a best-estimate containment failure pressure (~3 times design pressure), which implies that sprays are not required to prevent containment overpressure.
2. Fan coolers have no effect for large LOCAs.
3. Assume that the success state of the ECCS and containment spray trains occurs in a similar manner, i.e., can have (a) two ECCS trains and two spray trains or (b) one ECCS train and one spray train.
4. If both containment spray injection trains fail, both containment spray recirculation trains fail.
5. If ECCS recirculation has heat exchangers, then containment spray and fan coolers are not required [for example, Comanche Peak (large dry) and DC Cook (ice condenser) have ECCS heat exchangers, whereas Surry (subatmospheric) does not].
6. High-pressure ECCS recirculation must be piggybacked off low-pressure ECCS recirculation; thus, if heat removal is in ECCS for low-head recirculation, it is also in ECCS for high-head recirculation.
7. Failure of containment isolation is not modeled with regard to core cooling (a) is small relative contributor to core melt and (2) is not considered in most PRA front-end models.
8. If containment spray injection fails, so does containment recirculation spray.
9. The effect of containment systems on thermal-hydraulic state of sump is not of primary concern (e.g., whether the sump is saturated or subcooled) relative to other debris concerns (e.g., flow from sump).
10. Accumulators are a second-order effect and are not included in event tree.
11. One train of the low-head ECCS is 3000 gal./min (one pump per train); one train of the spray is 6000 gal./min (two pumps per train).
12. Assume that the switchover time for the ice condenser plant is 10 min if all ECCS and containment spray equipment operates; basis: (a) DC Cook IPE, p. 3-155, switchover time for LLOCA = 20 min (b) PWR survey – Sequoyah = 30 min, Watts Bar = 10 min (note: expect Sequoyah and Watts Bar to have similar times because the plants are similar – difference in cited switchover time may be in how data are reported (i.e., number of operable trains assumed).
13. Failure to trip reactor for transients and small and medium LOCAs is a small failure probability and is not included in the event tree.
14. Assume fan coolers cannot prevent spray actuation (LOCA size $\geq$2 in.); this would apply to SLOCA-3 and MLOCA and feed and bleed cooling with any size LOCA or transient.
15. Rapid depressurization to go to RHR SDC before switchover from ECCS injection to recirculation is possible with secondary cooling (steam generator cooling) for SLOCA-2 and SLOCA-3; rapid depressurization to go to RHR SDC before switchover from ECCS injection to recirculation is not possible with feed and bleed (no steam generator heat removal).
16. Cooling with either secondary cooling or feed and bleed not required; hole is sufficiently large. Also, hole is sufficiently large such that depressurization to RHR/SDC possible without using steam generator cooling (MLOCA).
17. For subatmospheric containment plants, require one containment spray recirculation heat exchanger train for core cooling because ECCS systems have no heat exchangers; other non-subatmospheric designs (i.e., CE plants) may have similar characteristics.
18. Assume fan coolers can prevent actuation of containment spray for large dry containment following SLOCA-2 if design has fan coolers operational following ECCS actuation signal and if high-high containment spray set point is not low.
19. Assume fan coolers cannot prevent containment spray actuation for ice condenser and subatmospheric designs.
20. Assume that feed and bleed can be accomplished with one 2-in. PORV.

ATTACHMENT C

CONDITIONAL FAILURE PROBABILITIES FOR SUMP FAILURE
(69 Cases—Each Sequence)

Parametric	LLOCA			MLOCA & SLOCA_3			SLOCA_2							TRANS
Case ID	Seq 2	Seq 4	Seq 7	Seq 2	Seq 4	Seq 7	Seq 2	Seq 5	Seq 7	Seq 10	Seq 13	Seq 15	Seq 18	(all seq)
1	0.99	0.99	0.9	0.9	0.9	0.6	0.6	0.99	0.9	0.6	0.99	0.9	0.6	0.01
2	0.99	0.99	0.9	0.4	0.4	0.1	0.1	0.6	0.4	0.1	0.6	0.4	0.1	0.001
3	0.6	0.6	0.4	0.1	0.1	0.01	0.001	0.1	0.01	0.001	0.1	0.01	0.001	0.001
4	0.999	0.999	0.99	0.9	0.9	0.6	-	0.9	0.6	0.4	0.9	0.6	0.4	0.01
5	0.99	0.99	0.9	0.9	0.9	0.6	0.4	0.9	0.6	0.4	0.9	0.6	0.4	0.01
6	0.99	0.99	0.9	0.9	0.9	0.6	-	0.6	0.4	0.1	0.6	0.4	0.1	0.01
7	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.1	0.01	0.001	0.1	0.01	0.001	0.001
8	0.999	0.999	0.99	0.9	0.9	0.6	-	0.9	0.6	0.4	0.9	0.6	0.4	0.01
9	0.999	0.999	0.99	0.99	0.99	0.9	0.9	0.999	0.99	0.9	0.999	0.99	0.9	0.01
10	0.99	0.99	0.9	0.9	0.9	0.6	0.9	0.999	0.99	0.9	0.999	0.99	0.9	0.01
11	0.99	0.99	0.9	0.9	0.9	0.6	0.4	0.9	0.6	0.4	0.9	0.6	0.4	0.01
12	0.9	0.9	0.6	0.9	0.9	0.6	0.01	0.4	0.1	0.01	0.4	0.1	0.01	0.001
13	0.9	0.9	0.6	0.1	0.1	0.01	0.01	0.4	0.1	0.01	0.4	0.1	0.01	0.001
14	0.99	0.99	0.9	0.1	0.1	0.01	0.1	0.6	0.4	0.1	0.6	0.4	0.1	0.001
15	0.9	0.9	0.6	0.6	0.6	0.4	0.1	0.6	0.4	0.1	0.6	0.4	0.1	0.001
16	0.99	0.99	0.9	0.9	0.9	0.6	0.4	0.9	0.6	0.4	0.9	0.6	0.4	0.01
17	0.999	0.999	0.99	0.9	0.9	0.6	0.4	0.9	0.6	0.4	0.9	0.6	0.4	0.01
18	0.001	0.001	0.001	0.001	0.001	0.001	-	0.001	0.001	0.001	0.001	0.001	0.001	0.001
19	0.999	0.999	0.99	0.9	0.9	0.6	0.9	0.999	0.99	0.9	0.999	0.99	0.9	0.01
20	0.999	0.999	0.99	0.99	0.99	0.9	0.9	0.999	0.99	0.9	0.999	0.99	0.9	0.01
21	0.6	0.6	0.4	0.4	0.4	0.1	0.001	0.1	0.01	0.001	0.1	0.01	0.001	0.001
22	0.999	0.999	0.99	0.9	0.9	0.6	0.9	0.999	0.99	0.9	0.999	0.99	0.9	0.01
23	0.99	0.99	0.9	0.4	0.4	0.1	0.1	0.6	0.4	0.1	0.6	0.4	0.1	0.001

Parametric	LLOCA			MLOCA & SLOCA_3			SLOCA_2							TRANS
Case ID	Seq 2	Seq 4	Seq 7	Seq 2	Seq 4	Seq 7	Seq 2	Seq 5	Seq 7	Seq 10	Seq 13	Seq 15	Seq 18	(all seq)
24	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.1	0.01	0.001	0.1	0.01	0.001	0.001
25	0.9	0.9	0.6	0.4	0.4	0.1	0.01	0.4	0.1	0.01	0.4	0.1	0.01	0.001
26	0.99	0.99	0.9	0.9	0.9	0.6	0.4	0.9	0.6	0.4	0.9	0.6	0.4	0.01
27	0.9	0.9	0.6	0.6	0.6	0.4	0.6	0.99	0.9	0.6	0.99	0.9	0.6	0.01
28	0.99	0.99	0.9	0.9	0.9	0.6	0.6	0.99	0.9	0.6	0.99	0.9	0.6	0.01
29	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.1	0.01	0.001	0.1	0.01	0.001	0.001
30	0.9	0.9	0.6	0.1	0.1	0.01	0.4	0.9	0.6	0.4	0.9	0.6	0.4	0.001
31	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.1	0.01	0.001	0.1	0.01	0.001	0.001
32	0.999	-	-	0.9	-	-	-	0.9	0.6	0.4	0.9	-	-	0.01
33	0.9	0.9	0.6	0.6	0.6	0.4	0.1	0.6	0.4	0.1	0.6	0.4	0.1	0.001
34	0.9	0.9	0.6	0.1	0.1	0.01	0.1	0.6	0.4	0.1	0.6	0.4	0.1	0.001
35	0.99	0.99	0.9	0.9	0.9	0.6	0.4	0.9	0.6	0.4	0.9	0.6	0.4	0.01
36	0.99	0.99	0.9	0.9	0.9	0.6	0.9	0.999	0.99	0.9	0.999	0.99	0.9	0.01
37	0.999	-	-	0.9	-	-	-	0.9	0.6	0.4	0.9	-	-	0.01
38	0.6	0.6	0.4	0.1	0.1	0.01	0.001	0.1	0.01	0.001	0.1	0.01	0.001	0.001
39	0.99	0.99	0.9	0.4	0.4	0.1	0.001	0.1	0.01	0.001	0.1	0.01	0.001	0.001
40	0.9	-	-	0.1	-	-	-	0.1	0.01	0.001	0.1	-	-	0.001
41	0.6	0.6	0.4	0.1	0.1	0.01	-	0.1	0.01	0.001	0.1	0.01	0.001	0.001
42	0.99	0.99	0.9	0.9	0.9	0.6	0.6	0.99	0.9	0.6	0.99	0.9	0.6	0.01
43	0.9	0.9	0.6	0.1	0.1	0.01	0.01	0.4	0.1	0.01	0.4	0.1	0.01	0.001
44	0.9	0.9	0.6	0.1	0.1	0.01	0.01	0.4	0.1	0.01	0.4	0.1	0.01	0.001
45	0.9	0.9	0.6	0.9	0.9	0.6	0.4	0.9	0.6	0.4	0.9	0.6	0.4	0.01
46	0.9	0.9	0.6	0.4	0.4	0.1	0.001	0.1	0.01	0.001	0.1	0.01	0.001	0.001

Parametric	LLOCA			MLOCA & SLOCA_3			SLOCA_2							TRANS
Case ID	Seq 2	Seq 4	Seq 7	Seq 2	Seq 4	Seq 7	Seq 2	Seq 5	Seq 7	Seq 10	Seq 13	Seq 15	Seq 18	(all seq)
47	0.999	0.999	0.99	0.9	0.9	0.6	0.9	0.999	0.99	0.9	0.999	0.99	0.9	0.01
48	0.999	-	-	0.9	-	-	-	0.9	0.6	0.4	0.9	-	-	0.01
49	0.001	0.001	0.001	0.001	0.001	0.001	-	0.001	0.001	0.001	0.001	0.001	0.001	0.001
50	0.4	0.4	0.1	0.1	0.1	0.01	-	0.1	0.01	0.001	0.1	0.01	0.001	0.001
51	0.99	0.99	0.9	0.9	0.9	0.6	0.4	0.9	0.6	0.4	0.9	0.6	0.4	0.01
52	0.6	0.6	0.4	0.1	0.1	0.01	0.001	0.1	0.01	0.001	0.1	0.01	0.001	0.001
53	0.99	0.99	0.9	0.9	0.9	0.6	-	0.6	0.4	0.1	0.6	0.4	0.1	0.01
54	0.99	0.99	0.9	0.6	0.6	0.4	0.6	0.99	0.9	0.6	0.99	0.9	0.6	0.01
55	0.9	0.9	0.6	0.6	0.6	0.4	0.01	0.4	0.1	0.01	0.4	0.1	0.01	0.001
56	0.9	0.9	0.6	0.1	0.1	0.01	0.01	0.4	0.1	0.01	0.4	0.1	0.01	0.001
57	0.9	0.9	0.6	0.1	0.1	0.01	0.01	0.4	0.1	0.01	0.4	0.1	0.01	0.001
58	0.99	-	-	0.9	-	-	-	0.9	0.6	0.4	0.9	-	-	0.01
59	0.999	-	-	0.9	-	-	-	0.9	0.6	0.4	0.9	-	-	0.01
60	0.99	0.99	0.9	0.6	0.6	0.4	0.1	0.6	0.4	0.1	0.6	0.4	0.1	0.001
61	0.6	0.6	0.4	0.1	0.1	0.01	0.1	0.6	0.4	0.1	0.6	0.4	0.1	0.001
62	0.99	0.99	0.9	0.9	0.9	0.6	0.9	0.999	0.99	0.9	0.999	0.99	0.9	0.01
63	0.99	0.99	0.9	0.9	0.9	0.6	0.4	0.9	0.6	0.4	0.9	0.6	0.4	0.01
64	0.001	0.001	0.001	0.001	0.001	0.001	-	0.001	0.001	0.001	0.001	0.001	0.001	0.001
65	0.99	0.99	0.9	0.9	0.9	0.6	0.4	0.9	0.6	0.4	0.9	0.6	0.4	0.01
66	0.001	-	-	0.001	-	-	-	0.001	0.001	0.001	0.001	-	-	0.001
67	0.9	0.9	0.6	0.1	0.1	0.01	0.001	0.1	0.01	0.001	0.1	0.01	0.001	0.001
68	0.9	0.9	0.6	0.1	0.1	0.01	0.001	0.1	0.01	0.001	0.1	0.01	0.001	0.001
69	0.6	0.6	0.4	0.1	0.1	0.01	0.01	0.4	0.1	0.01	0.4	0.1	0.01	0.001

ATTACHMENT D
SPREADSHEET OF RESULTS

No Debris

Type	ID	LLOCA trad	LLOCA LBB	MLOCA trad	MLOCA LBB	S3LOCA trad	S3LOCA LBB	S2LOCA trad	S2LOCA LBB	PORV	LOFW	Sum by Plant trad	Sum by Plant LBB
Large Dry	1	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	2	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	3	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	5	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	7	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	9	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	10	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	11	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	12	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	13	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	14	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	15	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	16	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	17	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	19	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	20	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	21	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	22	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	23	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	24	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	25	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	26	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	27	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	28	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	29	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	30	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	31	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	33	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	34	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	35	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	36	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	38	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	39	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	42	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	43	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	44	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	45	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	46	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	47	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	51	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	52	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	54	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	55	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06

	56	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	57	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	60	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	61	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	62	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	63	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	65	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	67	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	68	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
	69	3.500E-06	2.520E-08	7.010E-06	1.330E-07	1.000E-06	2.220E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	1.491E-05	3.041E-06
Sub Sum												7.902E-04	1.612E-04
Avg												1.491E-05	3.041E-06
Ice Cond	4	3.500E-06	2.520E-08	2.000E-06	3.800E-08	1.000E-06	2.200E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	9.900E-06	2.946E-06
	6	3.500E-06	2.520E-08	2.000E-06	3.800E-08	1.000E-06	2.200E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	9.900E-06	2.946E-06
	8	3.500E-06	2.520E-08	2.000E-06	3.800E-08	1.000E-06	2.200E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	9.900E-06	2.946E-06
	18	3.500E-06	2.520E-08	2.000E-06	3.800E-08	1.000E-06	2.200E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	9.900E-06	2.946E-06
	41	3.500E-06	2.520E-08	2.000E-06	3.800E-08	1.000E-06	2.200E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	9.900E-06	2.946E-06
	49	3.500E-06	2.520E-08	2.000E-06	3.800E-08	1.000E-06	2.200E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	9.900E-06	2.946E-06
	50	3.500E-06	2.520E-08	2.000E-06	3.800E-08	1.000E-06	2.200E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	9.900E-06	2.946E-06
	53	3.500E-06	2.520E-08	2.000E-06	3.800E-08	1.000E-06	2.200E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	9.900E-06	2.946E-06
	64	3.500E-06	2.520E-08	2.000E-06	3.800E-08	1.000E-06	2.200E-08	1.000E-06	4.610E-07	2.000E-06	4.000E-07	9.900E-06	2.946E-06
Sub Sum												8.910E-05	2.652E-05
Avg												9.900E-06	2.946E-06
SubAtmos	32	4.500E-06	3.240E-08	4.00E-06	7.60E-08	2.000E-06	4.400E-08	1.500E-06	6.910E-07	4.000E-06	6.000E-07	1.660E-05	5.443E-06
	37	4.500E-06	3.240E-08	4.00E-06	7.60E-08	2.000E-06	4.400E-08	1.500E-06	6.910E-07	4.000E-06	6.000E-07	1.660E-05	5.443E-06
	40	4.500E-06	3.240E-08	4.00E-06	7.60E-08	2.000E-06	4.400E-08	1.500E-06	6.910E-07	4.000E-06	6.000E-07	1.660E-05	5.443E-06
	48	4.500E-06	3.240E-08	4.00E-06	7.60E-08	2.000E-06	4.400E-08	1.500E-06	6.910E-07	4.000E-06	6.000E-07	1.660E-05	5.443E-06
	58	4.500E-06	3.240E-08	4.00E-06	7.60E-08	2.000E-06	4.400E-08	1.500E-06	6.910E-07	4.000E-06	6.000E-07	1.660E-05	5.443E-06
	59	4.500E-06	3.240E-08	4.00E-06	7.60E-08	2.000E-06	4.400E-08	1.500E-06	6.910E-07	4.000E-06	6.000E-07	1.660E-05	5.443E-06
	66	4.500E-06	3.240E-08	4.00E-06	7.60E-08	2.000E-06	4.400E-08	1.500E-06	6.910E-07	4.000E-06	6.000E-07	1.660E-05	5.443E-06
Sub Sum												1.162E-04	3.810E-05
Avg												1.660E-05	5.443E-06

Debris Type	ID	LLOCA trad	LLOCA LBB	MLOCA trad	MLOCA LBB	S3LOCA trad	S3LOCA LBB	S2LOCA trad	S2LOCA LBB	PORV	LOFW	Sum by Plant trad	Sum by Plant LBB
Large Dry	1	4.990E-04	3.600E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	4.390E-04	2.020E-04	1.500E-05	1.300E-06	2.315E-03	2.491E-04
	2	4.990E-04	3.600E-06	4.080E-04	7.740E-06	2.010E-04	4.430E-06	2.260E-04	1.040E-04	6.010E-06	4.000E-07	1.340E-03	1.262E-04
	3	3.040E-04	2.190E-06	1.070E-04	2.040E-06	5.110E-05	1.120E-06	3.620E-05	1.670E-05	6.010E-06	4.000E-07	5.047E-04	2.846E-05
	5	4.990E-04	3.600E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	3.770E-04	1.730E-04	1.500E-05	1.300E-06	2.253E-03	2.201E-04
	7	4.900E-06	2.880E-08	8.010E-06	1.520E-07	1.500E-06	3.300E-08	3.620E-05	1.670E-05	6.010E-06	4.000E-07	5.702E-05	2.332E-05
	9	5.040E-04	3.630E-06	9.990E-04	1.900E-05	4.970E-04	1.090E-05	4.870E-04	2.240E-04	1.500E-05	1.300E-06	2.503E-03	2.738E-04
	10	4.990E-04	3.600E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	4.870E-04	2.240E-04	1.500E-05	1.300E-06	2.363E-03	2.711E-04
	11	4.990E-04	3.600E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	3.770E-04	1.730E-04	1.500E-05	1.300E-06	2.253E-03	2.201E-04
	12	4.540E-04	3.270E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	1.430E-04	6.570E-05	6.010E-06	4.000E-07	1.964E-03	1.026E-04
	13	4.540E-04	3.270E-06	1.070E-04	2.040E-06	5.110E-05	1.120E-06	1.430E-04	6.570E-05	6.010E-06	4.000E-07	7.615E-04	7.854E-05
	14	4.990E-04	3.600E-06	1.070E-04	2.040E-06	5.110E-05	1.120E-06	2.260E-04	1.040E-04	6.010E-06	4.000E-07	8.895E-04	1.172E-04
	15	4.540E-04	3.270E-06	6.080E-04	1.150E-05	3.020E-04	6.630E-06	2.260E-04	1.040E-04	6.010E-06	4.000E-07	1.596E-03	1.318E-04
	16	4.990E-04	3.600E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	3.770E-04	1.730E-04	1.500E-05	1.300E-06	2.253E-03	2.201E-04
	17	5.040E-04	3.630E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	3.770E-04	1.730E-04	1.500E-05	1.300E-06	2.258E-03	2.202E-04
	19	5.040E-04	3.630E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	4.870E-04	2.240E-04	1.500E-05	1.300E-06	2.368E-03	2.712E-04
	20	5.040E-04	3.630E-06	9.990E-04	1.900E-05	4.970E-04	1.090E-05	4.870E-04	2.240E-04	1.500E-05	1.300E-06	2.503E-03	2.738E-04
	21	3.040E-04	2.190E-06	4.080E-04	7.740E-06	2.010E-04	4.430E-06	3.620E-05	1.670E-05	6.010E-06	4.000E-07	9.556E-04	3.747E-05
	22	5.040E-04	3.630E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	4.870E-04	2.240E-04	1.500E-05	1.300E-06	2.368E-03	2.712E-04
	23	4.990E-04	3.600E-06	4.080E-04	7.740E-06	2.010E-04	4.430E-06	2.260E-04	1.040E-04	6.010E-06	4.000E-07	1.340E-03	1.262E-04
	24	4.900E-06	2.880E-08	8.010E-06	1.520E-07	1.500E-06	3.300E-08	3.620E-05	1.670E-05	6.010E-06	4.000E-07	5.702E-05	2.332E-05
	25	4.540E-04	3.270E-06	4.080E-04	7.740E-06	2.010E-04	4.430E-06	1.430E-04	6.570E-05	6.010E-06	4.000E-07	1.212E-03	8.755E-05
	26	4.990E-04	3.600E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	3.770E-04	1.730E-04	1.500E-05	1.300E-06	2.253E-03	2.201E-04
	27	4.540E-04	3.270E-06	6.080E-04	1.150E-05	3.020E-04	6.630E-06	4.390E-04	2.020E-04	1.500E-05	1.300E-06	1.819E-03	2.397E-04
	28	4.990E-04	3.600E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	4.390E-04	2.020E-04	1.500E-05	1.300E-06	2.315E-03	2.491E-04
	29	4.900E-06	2.880E-08	8.010E-06	1.520E-07	1.500E-06	3.300E-08	3.620E-05	1.670E-05	6.010E-06	4.000E-07	5.702E-05	2.332E-05
	30	4.540E-04	3.270E-06	1.070E-04	2.040E-06	5.110E-05	1.120E-06	3.770E-04	1.730E-04	6.010E-06	4.000E-07	9.955E-04	1.858E-04
	31	4.900E-06	2.880E-08	8.010E-06	1.520E-07	1.500E-06	3.300E-08	3.620E-05	1.670E-05	6.010E-06	4.000E-07	5.702E-05	2.332E-05
	33	4.540E-04	3.270E-06	6.080E-04	1.150E-05	3.020E-04	6.630E-06	2.260E-04	1.040E-04	6.010E-06	4.000E-07	1.596E-03	1.318E-04
	34	4.540E-04	3.270E-06	1.070E-04	2.040E-06	5.110E-05	1.120E-06	2.260E-04	1.040E-04	6.010E-06	4.000E-07	8.445E-04	1.168E-04
	35	4.990E-04	3.600E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	3.770E-04	1.730E-04	1.500E-05	1.300E-06	2.253E-03	2.201E-04
	36	4.990E-04	3.600E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	4.870E-04	2.240E-04	1.500E-05	1.300E-06	2.363E-03	2.711E-04
	38	3.040E-04	2.190E-06	1.070E-04	2.040E-06	5.110E-05	1.120E-06	3.620E-05	1.670E-05	6.010E-06	4.000E-07	5.047E-04	2.846E-05
	39	4.990E-04	3.600E-06	4.080E-04	7.740E-06	2.010E-04	4.430E-06	3.620E-05	1.670E-05	6.010E-06	4.000E-07	1.151E-03	3.888E-05
	42	4.990E-04	3.600E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	4.390E-04	2.020E-04	1.500E-05	1.300E-06	2.315E-03	2.491E-04
	43	4.540E-04	3.270E-06	1.070E-04	2.040E-06	5.110E-05	1.120E-06	1.430E-04	6.570E-05	6.010E-06	4.000E-07	7.615E-04	7.854E-05
	44	4.540E-04	3.270E-06	1.070E-04	2.040E-06	5.110E-05	1.120E-06	1.430E-04	6.570E-05	6.010E-06	4.000E-07	7.615E-04	7.854E-05
	45	4.540E-04	3.270E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	3.770E-04	1.730E-04	1.500E-05	1.300E-06	2.208E-03	2.198E-04
	46	4.540E-04	3.270E-06	4.080E-04	7.740E-06	2.010E-04	4.430E-06	3.620E-05	1.670E-05	6.010E-06	4.000E-07	1.106E-03	3.855E-05
	47	5.040E-04	3.630E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	4.870E-04	2.240E-04	1.500E-05	1.300E-06	2.368E-03	2.712E-04
	51	4.990E-04	3.600E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	3.770E-04	1.730E-04	1.500E-05	1.300E-06	2.253E-03	2.201E-04
	52	3.040E-04	2.190E-06	1.070E-04	2.040E-06	5.110E-05	1.120E-06	3.620E-05	1.670E-05	6.010E-06	4.000E-07	5.047E-04	2.846E-05
	54	4.990E-04	3.600E-06	6.080E-04	1.150E-05	3.020E-04	6.630E-06	4.390E-04	2.020E-04	1.500E-05	1.300E-06	1.864E-03	2.400E-04
	55	4.540E-04	3.270E-06	6.080E-04	1.150E-05	3.020E-04	6.630E-06	1.430E-04	6.570E-05	6.010E-06	4.000E-07	1.513E-03	9.351E-05

	56	4.540E-04	3.270E-06	1.070E-04	2.040E-06	5.110E-05	1.120E-06	1.430E-04	6.570E-05	6.010E-06	4.000E-07	7.615E-04	7.854E-05
	57	4.540E-04	3.270E-06	1.070E-04	2.040E-06	5.110E-05	1.120E-06	1.430E-04	6.570E-05	6.010E-06	4.000E-07	7.615E-04	7.854E-05
	60	4.990E-04	3.600E-06	6.080E-04	1.150E-05	3.020E-04	6.630E-06	2.260E-04	1.040E-04	6.010E-06	4.000E-07	1.641E-03	1.321E-04
	61	3.040E-04	2.190E-06	1.070E-04	2.040E-06	5.110E-05	1.120E-06	2.260E-04	1.040E-04	6.010E-06	4.000E-07	6.945E-04	1.158E-04
	62	4.990E-04	3.600E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	4.870E-04	2.240E-04	1.500E-05	1.300E-06	2.363E-03	2.711E-04
	63	4.990E-04	3.600E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	3.770E-04	1.730E-04	1.500E-05	1.300E-06	2.253E-03	2.201E-04
	65	4.990E-04	3.600E-06	9.090E-04	1.730E-05	4.52E-04	9.94E-06	3.770E-04	1.730E-04	1.500E-05	1.300E-06	2.253E-03	2.201E-04
	67	4.540E-04	3.270E-06	1.070E-04	2.040E-06	5.110E-05	1.120E-06	3.620E-05	1.670E-05	6.010E-06	4.000E-07	6.547E-04	2.954E-05
	68	4.540E-04	3.270E-06	1.070E-04	2.040E-06	5.110E-05	1.120E-06	3.620E-05	1.670E-05	6.010E-06	4.000E-07	6.547E-04	2.954E-05
	69	3.040E-04	2.190E-06	1.070E-04	2.040E-06	5.110E-05	1.120E-06	1.430E-04	6.570E-05	6.010E-06	4.000E-07	6.115E-04	7.746E-05
Sub Sum												7.864E-02	7.893E-03
Avg												1.484E-03	1.489E-04
Ice Cond	4	5.000E-04	3.600E-06	9.040E-04	1.720E-05	4.520E-04	9.940E-06	4.520E-04	2.080E-04	1.100E-05	1.300E-06	2.320E-03	2.510E-04
	6	4.990E-04	3.600E-06	9.040E-04	1.720E-05	4.520E-04	9.940E-06	3.020E-04	1.390E-04	1.100E-05	1.300E-06	2.169E-03	1.820E-04
	8	5.000E-04	3.600E-06	9.040E-04	1.720E-05	4.520E-04	9.940E-06	4.520E-04	2.080E-04	1.100E-05	1.300E-06	2.320E-03	2.510E-04
	18	4.000E-06	2.880E-08	3.000E-06	5.710E-08	1.500E-06	3.300E-08	1.500E-06	6.920E-07	2.000E-06	4.000E-07	1.240E-05	3.211E-06
	41	3.040E-04	2.190E-06	1.020E-04	1.900E-08	5.110E-05	1.120E-06	5.110E-05	2.350E-05	2.000E-06	4.000E-07	5.106E-04	2.923E-05
	49	4.000E-06	2.880E-08	3.000E-06	5.710E-08	1.500E-06	3.300E-08	1.500E-06	6.920E-07	2.000E-06	4.000E-07	1.240E-05	3.211E-06
	50	2.040E-04	1.470E-06	1.020E-04	1.900E-08	5.110E-05	1.120E-06	5.110E-05	2.350E-05	2.000E-06	4.000E-07	4.106E-04	2.851E-05
	53	4.990E-04	3.600E-06	9.040E-04	1.720E-05	4.520E-04	9.940E-06	3.020E-04	1.390E-04	1.100E-05	1.300E-06	2.169E-03	1.820E-04
	64	4.000E-06	2.880E-08	3.000E-06	5.710E-08	1.500E-06	3.300E-08	1.500E-06	6.920E-07	2.000E-06	4.000E-07	1.240E-05	3.211E-06
Sub Sum												9.938E-03	9.335E-04
Avg												1.104E-03	1.037E-04
SubAtmos	32	5.040E-04	3.630E-06	9.040E-04	1.720E-05	4.520E-04	9.940E-06	4.520E-04	2.080E-04	1.400E-05	1.600E-06	2.328E-03	2.544E-04
	37	5.040E-04	3.630E-06	9.040E-04	1.720E-05	4.520E-04	9.940E-06	4.520E-04	2.080E-04	1.400E-05	1.600E-06	2.328E-03	2.544E-04
	40	4.550E-04	3.270E-06	1.040E-04	1.980E-06	5.200E-05	1.140E-06	5.150E-05	2.370E-05	5.000E-06	7.000E-07	6.682E-04	3.579E-05
	48	5.040E-04	3.630E-06	9.040E-04	1.720E-05	4.520E-04	9.940E-06	4.520E-04	2.080E-04	1.400E-05	1.600E-06	2.328E-03	2.544E-04
	58	5.000E-04	3.630E-06	9.040E-04	1.720E-05	4.520E-04	9.940E-06	1.950E-06	8.990E-07	1.400E-05	1.600E-06	1.874E-03	4.727E-05
	59	5.040E-04	3.630E-06	9.040E-04	1.720E-05	4.520E-04	9.940E-06	4.520E-04	2.080E-04	1.400E-05	1.600E-06	2.328E-03	2.544E-04
	66	5.000E-06	3.600E-08	5.000E-06	9.500E-08	2.500E-06	5.500E-08	4.520E-04	2.080E-04	5.000E-06	7.000E-07	4.702E-04	2.139E-04
Sub Sum												1.232E-02	1.314E-03
Avg												1.760E-03	1.878E-04
Grand Sum												1.009E-01	1.014E-02
Avg												1.462E-03	1.470E-04

ATTACHMENT E

LETTER REPORT:
TECHNICAL APPROACH FOR RISK ASSESSMENT OF PWR SUMP SCREEN BLOCKAGE

Technical Letter Report

GSI-191 Study: Technical Approach for Risk Assessment of PWR Sump-Screen Blockage

July 23, 2001, Revision 3

Prepared by

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Both pressurized water reactors (PWRs) and boiling water reactors (BWRs) rely on the Emergency Core Cooling System (ECCS) to inject water into the reactor core following a postulated break in the reactor primary piping. This accident, commonly referred to as a loss-of-coolant accident (LOCA), and the ability of the ECCS to provide reliable long-term core cooling following a LOCA form the primary basis for licensing of nuclear power plants by the U.S. Nuclear Regulatory Commission (NRC). The Code of Federal Regulations, 10 CFR 50.46, "Acceptance Criteria for Emergency Core-Cooling Systems for Light-Water Nuclear Power Reactors," requires that all operating reactors (PWRs and BWRs) be equipped with an ECCS that is designed to meet five criteria. One of those criteria is long-term cooling, a process by which core-decay heat is removed by ECCS recirculation water flow.

Damaged insulation and other debris generated by LOCA jets can impede or prevent the recirculation of water into the core in one of two ways. First, the accumulation of debris on sump screens (or strainers) can increase hydrodynamic resistance and thus reduce the net positive suction head (NPSH) available to the ECCS pumps drawing water from the sump. Reduction in the NPSH may result in ECCS pump cavitation, which in turn may degrade the ECCS's ability to provide long-term cooling. Second, the accumulation of debris at the sump screen or along flow paths on the containment floor may form dams that prevent or impede the flow of water into the sump. This may ultimately lead to a draw-down of water in the sump, which also can cause failure of ECCS recirculation.

The NRC recently completed a research program to study the potential for loss of the ECCS as a result of debris buildup on BWR suction strainers. Based on the results of that study and on experience gained during several operational events, the NRC requested that licensees evaluate their plants and, if necessary, make changes to prevent any detrimental effects from debris blockage(NRC Bulletin 96-03). All BWRs have since installed suction strainers with larger surface areas to ensure that debris blockage does not prevent or impede operation of the ECCS.

In light of the results from the BWR study, the NRC has opened Generic Safety Issue (GSI) 191, "Assessment of Debris Accumulation on PWR Sump Performance." The overall objective of the GSI-191 program is to carry out a research program similar in breadth and depth to the BWR study that investigates debris blockage of PWR sumps and determines if there is a need for remedial actions.

The Los Alamos National Laboratory (LANL) Technology and Safety Assessment Division (TSA) is supporting the NRC Office of Nuclear Regulatory Research (RES) in a multiyear, multiphase resolution of GSI-191. The LANL research has four technical objectives.

1. Determine if the transport and accumulation of debris in containment following a LOCA will impede operation of the ECCS.
2. If it is found that debris accumulation will impede ECCS operation in some or all PWRs, develop the technical basis for revising NRC regulations and/or guidance to ensure that debris accumulation in containment will not prevent ECCS operation.
3. Provide NRC technical reviewers with sufficient information on the phenomena involved in debris accumulation and how they affect ECCS operation to facilitate the review of any changes to plants that may be warranted.
4. Support the NRC staff in preparation for and during both public and internal meetings concerning the assessment of the effects of debris accumulation on ECCS operation.

One of the criteria that the NRC will use to judge the significance of debris blockage issues for PWRs is the incremental risk of core damage posed industry-wide by the potential loss of the ECCS. This is a comprehensive metric that requires (1) a review of plant-to-plant variability in sump design, containment layout, and Emergency Operating Procedures (EOPs); (2) a careful analysis of all possible reactor accident progressions and an attendant understanding of the time-dependent thermal hydraulics of nuclear reactor systems; (3) a predictive model of debris generation and transport that is both empirically and computationally based; and (4) a thorough description of head-loss phenomena at the sump screen to determine if ECCS recirculation requirements can be met with LOCA-generated debris present.

This paper continues a series of Technical Letter Reports (TLRs) that document the experimental observations, methodologies, and assumptions that are being developed to address the GSI-191 sump-blockage issue. Key elements of an integrated risk assessment methodology are presented here in a general discussion that emphasizes (1) systems-level event-tree models to capture the necessary details of accident progressions and (2) the interface between explicit systems-level events and implicit debris phenomenology simulations that will be needed to estimate the likelihood of ECCS sump availability during a LOCA. A principal objective of the risk assessment methodology is the ability to examine separately the risk effects of different system-failure criteria arising from either licensing-basis assumptions or design-basis plant responses, including alternative mitigation strategies that may be available to operators under EOPs. In many respects, including a rigorous examination of debris effects and the comparison of alternative failure criteria, this methodology is intended to broaden the scope of a conventional probabilistic risk assessment (PRA).

ACRONYMS

AS	Accident Sequence
BS	Break Set
BWR	Boiling Water Reactor
CDF	Core Damage Frequency
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CP	Conditional Probability
DP	Debris Phenomena
DS	Debris Set
ECCS	Emergency Core Cooling System
EOP	Emergency Operating Procedure
GSI	Generic Safety Issue
IPE	Individual Plant Examination
LAFW	Loss of Auxiliary Feedwater
LANL	Los Alamos National Laboratory
LBB	Leak Before Break
LERF	Large Early Release Frequency
LLOCA	Large-Sized Loss-of-Coolant Accident
LOCA	Loss-of-Coolant Accident
LOSP	Loss of Offsite Power
MLOCA	Medium-Sized Loss-of-Coolant Accident
NEI	Nuclear Electricity Institute
NPSHA	Net Positive Suction Head Available
NPSHR	Net Positive Suction Head Required
NRC	Nuclear Regulatory Commission
NRR	Nuclear Reactor Regulation (Office of)
NSSS	Nuclear Steam Supply Systems
PDC	Plant Design Characteristics
PORV	Pressure-Operated Relief Valves
PRA	Probabilistic Risk Analysis
PRT	Pressurizer Relief Tank
PSC	Plant System conditions
PSLB	Pressurizer Surge-Line Break
PWR	Pressurized Water Reactor
RCP	Reactor Coolant Pump
RCS	Reactor Cooling System
RES	Nuclear Regulatory Research (Office of)
SAR	Safety Analysis Report
SCS	Shutdown Cooling System
SGTR	Steam Generator Tube Rupture
SLOCA	Small-Sized Loss-of-Coolant Accident
SS	Sump State
TLR	Technical Letter Report
TRVFO	Transient with Relief Valve Failed Open
TSA	Technology and Safety Assessment

NOTATION

AS	Accident sequence
BS	Break set
CDF	Core damage frequency {yr^{-1}}
ΔCDF	Incremental change in CDF due to debris effects {yr^{-1}}
$CP_{ECCS\ FAIL\ DEBRIS}$	CP of ECCS failure due to debris effects {fraction}
$CP_{SUMP\ AVAIL\ DEBRIS}$	CP of sump availability given possible debris effects {fraction}
DS	Debris set
F_{Sump}	Frequency that ECCS sump is required {yr^{-1}}
$LERF$	Large early release frequency {yr^{-1}}
$\Delta LERF$	Incremental change in LERF due to debris effects {yr^{-1}}
$NPSHA$	Net positive suction head available {Pa}
$NPSHR$	Net positive suction head required {Pa}
$P_{Fail\ Sump\ Debris}$	Binary probability of sump failure for a completely specified accident sequence {0 or 1}

GSI-191 STUDY: TECHNICAL APPROACH FOR RISK ASSESSMENT OF PWR SUMP-SCREEN BLOCKAGE

1.0. INTRODUCTION

This paper summarizes the general approach developed by the Probabilistic Risk and Hazard Analysis Group (TSA-11) at Los Alamos National Laboratory (LANL) for quantifying the risk from debris-induced loss of the Emergency Core Cooling System (ECCS) recirculation sump in pressurized water reactors (PWRs). The purpose of the analysis was to estimate the effect of loss of the ECCS sump on the core-damage frequency (CDF) and the large early release frequency (LERF) for PWRs. Previous estimates of these metrics have not considered the possibility that insulation debris generated during a loss-of-coolant accident (LOCA) may be transported to the recirculation sump.[1] Potential debris accumulation and degraded sump performance are the principal concerns of Generic Safety Issue (GSI) 191, which this work directly supports.

The risk assessment method discussed here was presented at a Nuclear Regulatory Commission (NRC)-sponsored public meeting on March 22, 2000, at NRC Headquarters in Rockville, Maryland. The present expanded and refined report supercedes the previous draft letter report written in April 2000. Although the methodology is presented here generically, it is being developed with the cooperation of two specific volunteer plants to demonstrate its applicability and practicality.

This assessment examines the industry-wide risk of PWR sump-screen blockage, including both large-dry and ice-condenser containment designs with nuclear steam supply systems (NSSS) originally provided by Westinghouse, Babcock and Wilcox, and Combustion Engineering. The participation of volunteer plants with each of these designs and two different vendors (Westinghouse and Combustion Engineering) helps to ensure that templates of all primary safety systems are built into the risk assessment methodology.

Many sources of information are incorporated into this risk assessment. Probabilistic risk analysis (PRA) information embodied in individual plant examination (IPE) studies will be used to obtain plant-specific information. IPEs for the following plants have been gathered: D.C. Cook, South Texas, Oconee, Byron/Braidwood, Haddam Neck, Salem, Watts Bar, Diablo Canyon, and Indian Point 3. Safety Analysis Reports (SARs) also were used. Selected information from the following SARs has been collected: D.C. Cook, South Texas, Zion, San Onofre, Byron/Braidwood, Surry, and Oconee. If necessary, information from other IPEs and SARs will be collected and used as needed.

Other sources of data that will be used in the evaluation of component and system failures include WASH-1400, existing PRAs, and NUREG/CR-5750; information from emergency operating procedures (EOPs) will be used in evaluating potential operator actions that may reduce the likelihood of sump loss.

This risk assessment method is being developed concurrently with ongoing studies of debris generation, containment-pool transport, and sump-screen head loss. Both deterministic and probabilistic models of these phenomena will be needed to assign the conditional probability of ECCS availability for any given accident sequence. Debris phenomenology will be the subject of several separate technical letter reports that support GSI-191, so the present discussion only defines the anticipated interface between event trees (used in the risk assessment to describe the reactor system response) and the detailed simulation of debris transport and accumulation.

2.0. SCOPE OF RISK ANALYSIS TASK

The risk analysis task discussed in this paper is one part of the overall NRC/LANL program for analyzing the effects of debris blockage on the ECCS sump in PWRs. A previous technical letter report to the NRC titled "Selection of Pressurized Water Reactor Accident Sequences for Evaluation of the Effect of Debris in the Sump" established the groundwork for a risk assessment methodology by examining all identified accident sequences for all

[1] Some existing IPE studies examined the possibility of sump blockage but assigned very low probabilities of failure (<1E-3 per demand).

operating PWR reactor designs. Some general conclusions from this study, which helped to determine the appropriate scope of the risk assessment, are listed below.

- There are no available probabilistic models for debris-induced failure of ECCS recirculation in PWRs. Although some IPEs addressed this eventuality, the failure probability data that they incorporated were not based on mechanistic determinations.
- The PWR sump-screen clogging issue is plant-specific. Any future probabilistic models of debris-induced failure of ECCS recirculation also will have to be plant-specific. A significant number of parametric and uncertainty analyses will have to be incorporated into any future analyses if the intent is to draw conclusions regarding the industry-wide risk significance of this issue.
- The probability and timing of ECCS-recirculation failure are strongly dependent on the LOCA size and discharge location inside containment. They also depend on the assumptions related to systems response. Considerations such as (a) licensing-basis plant response compared with design-basis plant systems response and (b) preferred mitigation strategies compared with alternate mitigation strategies should be addressed explicitly.
- Although, the debris-induced pressure drop across a congested sump screen generally should decrease with the size of the break, it appears that a significant head loss could occur even with medium and small LOCAs (for example, when calcium-silicate and fiber debris are generated in combination).
- The timing of ECCS-recirculation failure for smaller LOCAs allows more time for operator corrective actions. Containment spray actuation following a small-LOCA event plays an important role in the transport of debris to the sump, and at the same time, it affects the timing of ECCS recirculation failure.
- Although the most likely mechanism of debris-induced ECCS recirculation failure involves a pressure drop across the screen, other mechanisms are also possible (such as missile generation and screen penetration by debris, which could cause liquid flow restrictions in the core and pump operability or leak-tightness problems). These other effects are not part of this risk assessment, although it can be modified easily to draw insights regarding the risk significance of such concerns.
- Any future models of debris-induced failure of ECCS recirculation are expected to have large uncertainties associated with them, and uncertainty analyses should be an essential part of the risk assessment. The present study proposes an abbreviated uncertainty analysis, especially as it relates to systems response and PRA data. This approach may not capture important coupling that exists between the phenomenological, systems, and reactor-operator interfaces.

To address the above concerns and to fulfill the NRC risk analysis task assigned to LANL, the following subtasks will be completed.

1. Estimate the frequency of important initiating events that lead to a need for long-term cooling by recirculation.
2. For each volunteer plant, estimate
   - the *CDF* and change in *CDF* (ΔCDF) as a result of debris effects,
   - the *LERF* and change in *LERF* ($\Delta LERF$) as a result of debris effects, and
   - the conditional probability (CP) of ECCS failure as a result of debris effects ($CP_{ECCS\ FAIL\ DEBRIS}$).
3. Perform a sensitivity/parametric analysis for PWR plants in general that
   - captures plant design differences and
   - evaluates the importance of major differences that affect risk.

3.0. TECHNICAL APPROACH FOR EVALUATING RISK

3.1. Selection of Evaluation Tools

The following objectives were selected for the risk evaluation approach.

- Estimate *CDF*, ΔCDF, *LERF*, $\Delta LERF$, and $CP_{ECCS\ FAIL\ DEBRIS}$
- Differentiate among plant designs
- Be able to quantify numerous accident sequences at the systems level
- Be extensible to the component level

- Consider operator mitigation strategies
- Be quantifiable with both licensing-basis assumptions and "most likely" plant response
- Be able to quantify the effect of debris accumulation on the sump screen

Several attributes are desirable in the risk evaluation approach.

- State of the art
- Fast (computerized)
- Flexible, extensible, proven
- Acceptable to NRC
- Easy to understand conceptually
- Inclusive of sensitivity and uncertainty analysis capabilities

Based on the objectives and desirable attributes listed above, we recommend that the SAPHIRE software package be used to evaluate the risk. We recommend that plant-response models be developed using event trees defined at the systems level and that the systems-level models be flexible enough to incorporate traditional PRA data, newer PRA data, and plant-specific data. It is recommended that the evaluation models be extended to the component level using fault trees only as necessary to quantify the frequencies of specific events in the systems-level models.

3.2. Components of the Evaluation Process

The evaluation process (other than debris generation and transport phenomena, which are addressed later) has the following components.

1. Select accident sequences
2. Identify possible mitigation strategies
3. Estimate frequencies of initiating events
4. Account for licensing vs "most likely" plant systems response
5. Account for plant design differences

3.2.1. Selection of Accident Sequences. The criteria used to select specific accident sequences for evaluation include (1) the potential importance of the ECCS sump for mitigating an initiating event and (2) the potential of the accident to generate significant quantities of insulation debris, i.e., whether high-pressure fluids are released to containment. The metric used to measure the importance of the ECCS sump is the frequency with which it is required; specifically,

$$F_{sump} \equiv \text{frequency of accident-initiating event}$$
$$\times \text{ conditional probability sump is required for ECCS recirculation.}$$

Note that these criteria do not address the likelihood that the sump will be blocked by debris because that is the purpose of the follow-on evaluation of the selected sequences. The application of this metric was documented in an April 30, 1999, letter report to the NRC titled "Selection of Pressurized Water Reactor Accident Sequences for Evaluation of the Effect of Debris in the Sump."

Based on the earlier letter report and follow-on discussions with the NRC, the following accident sequences were selected for evaluation.

1. Loss of Offsite Power Followed by Loss of Auxiliary Feedwater (LOSP/LAFW)
2. Medium Loss-of-Coolant Accident (MLOCA)
3. Small Loss-of-Coolant Accident (SLOCA)
4. Large Loss-of-Coolant Accident (LLOCA)
5. Transient with Pressurizer Relief Valve Failed Open (TRVFO)
6. Pressurizer Surge-Line Break (PSLB)

Sequence 1 (LOSP/LAFW) is a transient that requires the use of "feed and bleed"[2] operator action because both main and auxiliary feedwater are lost. This sequence covers non-LOCA transients that evolve into feed-and-bleed scenarios in which the sump is used for long-term recirculation.

Sequences 2, 3, and 4 are LOCAs of various sizes for which the ECCS sump is required for ECCS recirculation. The timing of switchover from ECCS injection to ECCS recirculation and the specific ECCS recirculation pumps and recirculation flow rates differ among these three LOCAs.

Sequence 5 (TRVFO) is a precursor transient event that transitions into a LOCA. Two such transients were considered: (1) a failed-open pressurizer relief valve and (2) a reactor coolant pump (RCP) seal LOCA. The failed-open relief valve was selected for specific analysis because it is the more likely of the two accident scenarios.

Sequence 6 (PSLB) is a break in the pressurizer surge line. At the request of the NRC, sequence 6 was included because some plants may not meet the NRC criteria to credit leak before break[3] (LBB) for this piping system.

Sequences 1 and 5 share the common feature that venting occurs through a rupture disk of the pressurizer relief tank (PRT), which represents a specific location in the containment that may or not contain insulation. All other sequences discharge high-pressure water and steam at the point of the break. The full range of break locations for these sequences *must* be examined parametrically to account for possible debris generation.

3.2.2. Identification of Possible Mitigation Strategies. In the event of an accident or abnormal operating condition, the reactor operators may choose from several courses of action that reduce the severity of the event. These alternatives carry different likelihoods that the ECCS sump will be required to bring the plant to safe shutdown. To date, the following possible mitigation strategies have been identified based on the Nuclear Electricity Institute (NEI) survey of operating PWRs.

- Refill source of injection water and continue injection
  - Requires borated water
  - May overfill containment
- Depressurize Reactor Coolant System (RCS) and use Shutdown Cooling System (SCS)
  - There are limits on the rate of depressurization/cooldown
- Throttle flow through pumps that pull from sump
  - Counter to the safety philosophy of injecting as much water to the vessel as possible
  - May violate requirement to maintain subcooling margin

All potential mitigation strategies require consideration of the appropriate EOPs. Sources of information for consideration of potential mitigation strategies include the PWR plant survey (completed as part of the overall sump-blockage analysis effort—see the separate technical letter report) and EOPs for selected plants.

3.2.3. Estimation of Initiating-Event Frequencies. Two sources of initiating-event frequencies will be used.

- "Standard" PRA (from the WASH-1400 Reactor Safety Study through the more recent PRAs performed as part of the IPE program)
- "Newer" risk assessment values (incorporating LBB considerations)

The reason for using these different sources of data is to effect risk quantification using assumptions that span the range from most conservative estimates of initiating-event frequencies to the most realistic. Licensing bases

[2] "Feed and bleed" refers to a manual procedure for decay-heat removal where the operator periodically opens pressure-operated relief valves (PORVs) to bleed pressurized water from the RCS and then charges high-pressure safety injection pumps from the ECCS sump to feed water back to the RCS.

[3] Experimental tests have shown that RCS piping is susceptible to gradual degradation mechanisms such as wall and weld thinning that will introduce observable leaks long before a significant break occurs. It is argued that a rigorous ultrasound and optic inspection program can greatly reduce the estimated frequency of catastrophic failure.

examine the frequencies of each severe accident independently without regard to relative frequencies of occurrence. Traditional PRAs apply an equally conservative estimate of each accident initiation frequency and then compare the relative risk contributions of each. Recent considerations of LBB have attempted to replace recognized conservatism in the traditional break-frequency estimates with realism supported by experimental study.

Specific frequency data from these sources were included in the April 30, 1999, letter report to the NRC titled "Selection of Pressurized Water Reactor Accident Sequences for Evaluation of the Effect of Debris in the Sump." Table 1 is an excerpt from that letter report that lists frequency values from various sources.

3.2.4. Accounting for Licensing-Basis vs "Most Likely" Plant Systems Response. For the most part, licensing assumptions reflect a single-failure criterion that results in the availability of only one of two ECCS trains to provide core cooling during both the injection and recirculation phases of an accident and only one train of containment cooling with sprays and (possibly) fan coolers. Regulatory Guide 1.1 typically is applied, which does not credit the effect of containment pressurization on the net positive suction head available[4] (NPSHA) for the ECCS sump.

In contrast to the single-failure licensing criterion, the "most likely" (most probable) response is that all equipment will be available, which results in the operation of both trains of the ECCS and both trains of containment cooling. It is possible that the "most likely" plant response may result in a higher likelihood of sump loss than the licensing response because the "most likely" response requires increased flow from the sump that may increase debris transport and lead to a higher pressure drop across the sump screen. However, if fan coolers prevent the actuation set point for containment spray from being reached, the "most likely" response may result in a lower likelihood of sump loss because less volume will be required from the sump. In any case, the "most likely" response will result in an increased containment pressure that increases the NPSHA; this increase is not credited by the licensing bases. It is difficult to determine the effects of these assumptions on sump availability without a systematic examination of each alternative.

3.2.5. Accounting for Plant Design Differences. There are numerous important differences among the operating plants that affect the availability of the sump when debris is present. Some of the most important of these differences are as follows.

- Sump and pump characteristics
- Use of makeup pumps as part of the high-pressure ECCS
- Use of fan coolers for containment cooling
- Point of discharge of RCS safety valves, i.e., to the pressurizer quench tank or directly to containment
- Different actuation set points for containment spray
- Location of the sump relative to the steam-generator cavities where the largest amounts of debris might be generated
- Types and locations of insulation types used

After risk evaluations for the volunteer plants have been completed, the effect of the variability of important plant design differences will be captured through sensitivity analyses. The final ΔCDF and $\Delta LERF$ values will be expressed with a range that incorporates these differences. This approach for extrapolating specific results from the volunteer plants to the overall population of operating PWRs will address important design differences while minimizing the number of plants that must be modeled in detail.

[4]The inlet pressure head that is available to drive pump performance is determined by the depth of water above the inlet, the water temperature (density), and the pressure of the sealed containment environment among other factors. With the presumption that the summation is greater than 0, this total pressure is defined as the NPSHA. Pump performance improves with increasing NPSHA.

Table 1
Calculations Used to Estimate Frequency that Sump Will Be Required

Debris Concern Category	Accident Condition Type	Accident Condition Frequency (per year)				Conditional Probability of Requiring Sump w/o Special Strategy		F_{sump}, Frequency of Accident Condition Times CP of Requiring Sump (per year); (all sequences potentially generate debris)		Characterization of Potential Source of Debris
		IPE	Basis	Updated	Basis	Value	Basis Notes	IPE	Updated	
A	LLOCA	5E-04	a	5E-06	b	1		5E-04	5E-06	C1
A	MLOCA	1E-03	a	4E-05	b	1		1E-03	4E-05	C2
A	SLOCA (4)	1E-03	a	5E-04	b	1		1E-03	5E-04	C3
A	ISLOCA inside containment	1E-04	c			1		1E-04		C2
A	Transient that transitions to RCP seal LOCA	4E-05	d			1		4E-05		C3
A	Transient involving RCS valves opening and failing to reclose	4E-04	e			1		4E-04		C4
B	Small-small LOCA	1.3E-02	a			1E-03	h, 1, 2	1.3E-05		C4
B	Transients involving RCS valves opening and reclosing	1E-01				1E-03	h, 1, 2	1E-04		C4
B	Transients that discharge fluid into containment but do not evolve into LOCAs (e.g. MSLB, MLFB)	2.16E-03	a			1E-03	h, 1, 2	2.16E-06		C1
B	ATWS transients in which RCS valves reclose	1.3E-04	f			0	3			
C	(None identified at present time)									
D	Transients that do not discharge fluid into containment	8.4	a	1.2	b	1E-03	h	8.4E-03	1.2E-03	C4
D	Steam generator tube rupture (SGTR)	1E-02	a	7E-03	b	1E-03	h	1E-05	7E-06	C4
D	ISLOCA outside containment	2E-06	g			0	3	0		

Basis: (a) Indian Point 3 IPE list of generic values, IPE Table 3.3.1.1; (b) "Rates of Initiating Events at U. S. Nuclear Power Plants: 1987–1995," NUREG/CR-5750, February 1999. (c) based on estimated failure rate of inboard RHR shutdown cooling line isolation valve (see text for additional details); (d) based on estimated frequency of station blackout (SBO) and non-recovery of AC electrical power within 1 h (see text for additional details); (e) based on demand probabilities of PORV operation following a transient, along with probability that an open PORV will fail to reclose (see text for additional details); (f) based on Indian Point 3 IPE estimate of RPS failure probability of 1.6E-05 (see text for additional details); (g) Indian Point 3 IPE list of plant-specific values, IPE Table 3.3.1.1; (h) based on Indian Point 3 IPE loss of secondary cooling (see text for additional details).

Notes: (1) loss of steam generator cooling for decay heat removal, (2) debris from feed and bleed (potential), (3) cannot mitigate with sump, and (4) does not include random RCP seal failures—these failures will be addressed later.

Debris Concern Category: A = some debris/ECCS required, B = some debris/ECCS not required, C = no debris/ECCS required, D = no debris/ECCS not required.

Characterization of potential source of debris: (C1) large (C2) medium (C3) small (C4) debris from feed and bleed; quench tank rupture disk is source of fluid.

3.3. Use of Event Trees with Systems-Level Models

Analyses of event trees with the SAPHIRE computer code are fast. The use of event trees is acceptable to the NRC because event trees have been used extensively for reactor safety modeling since the 1970s. Event trees also are easy to understand conceptually. At the top level, an event tree provides a clear description of systems-level successes and failures through each accident sequence, which are defined by unique paths through the tree. At the top level, an event tree also quantifies each alternative accident sequence by the product of the initiating-event frequency and the subsequent systems-level conditional probabilities at each branch. The outcomes of each sequence quantified in this manner are called "endstates." The SAPHIRE framework has built-in capabilities for conducting sensitivity and uncertainty analyses on each endstate estimate.

A simple example event tree is shown in Fig. 1. The events on the tree are defined at the functional/systems level, and the use of various data sources and of detailed debris phenomena evaluations are both indicated on the figure. The first heading to the left is the initiating event with units of annual frequency (events per year). All other headings define subsequent events (sometimes called "top events") that have unitless probabilities of occurring during any particular accident sequence. Here, each endstate has been given a qualitative evaluation to assess the outcome of each possible accident sequence.

CDF is determined by the states of plant systems that are involved with keeping the reactor core cooled; core damage is postulated to occur when these systems are unavailable or do not function during a particular accident sequence. *LERF* is determined by the state of containment given a release of radionuclides from the core; a significant release is assumed to occur if containment has been breached in any way during a particular accident sequence.

To estimate *LERF* and *CDF*, the event trees will include containment-state information as well as core-cooling-state information in the set of top events for each tree, and the event-tree-sequence endstates will include both core- and containment-state designations. Figure 2 shows how *CDF* and *LERF* will be addressed at a simple conceptual level in the event trees. Event-tree endstates define all outcomes of an accident that are possible under the systems model. For example, the summation of all quantified events ending in core damage approximates the *CDF*.

The event trees will include the quantification of debris effects by using the conditional probabilities for failure of core/containment cooling during recirculation from the sump as explicit events on the trees. For a given accident sequence, this conditional probability is dependent on (a) the state of the plant as specified by the unique set of prior events in the sequence and (b) debris generation and transport phenomena. The first of these considerations is built into the event tree by quantifying the various systems-level branches in the tree. The second consideration will be addressed by using the results of phenomenological debris studies being performed in other tasks of the overall NRC/LANL program.

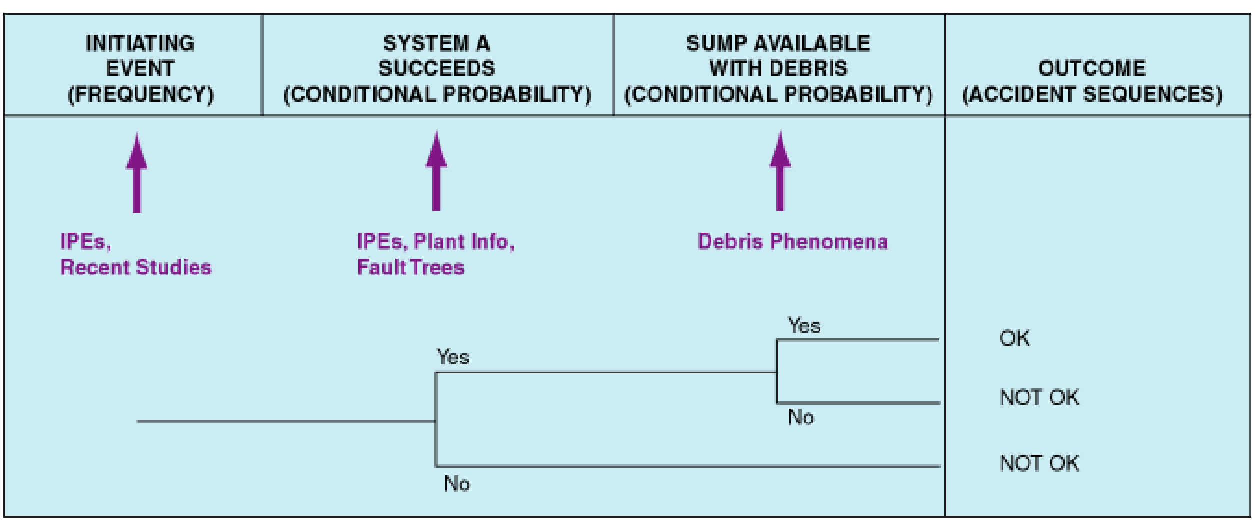

Fig. 1. A simple example event tree.

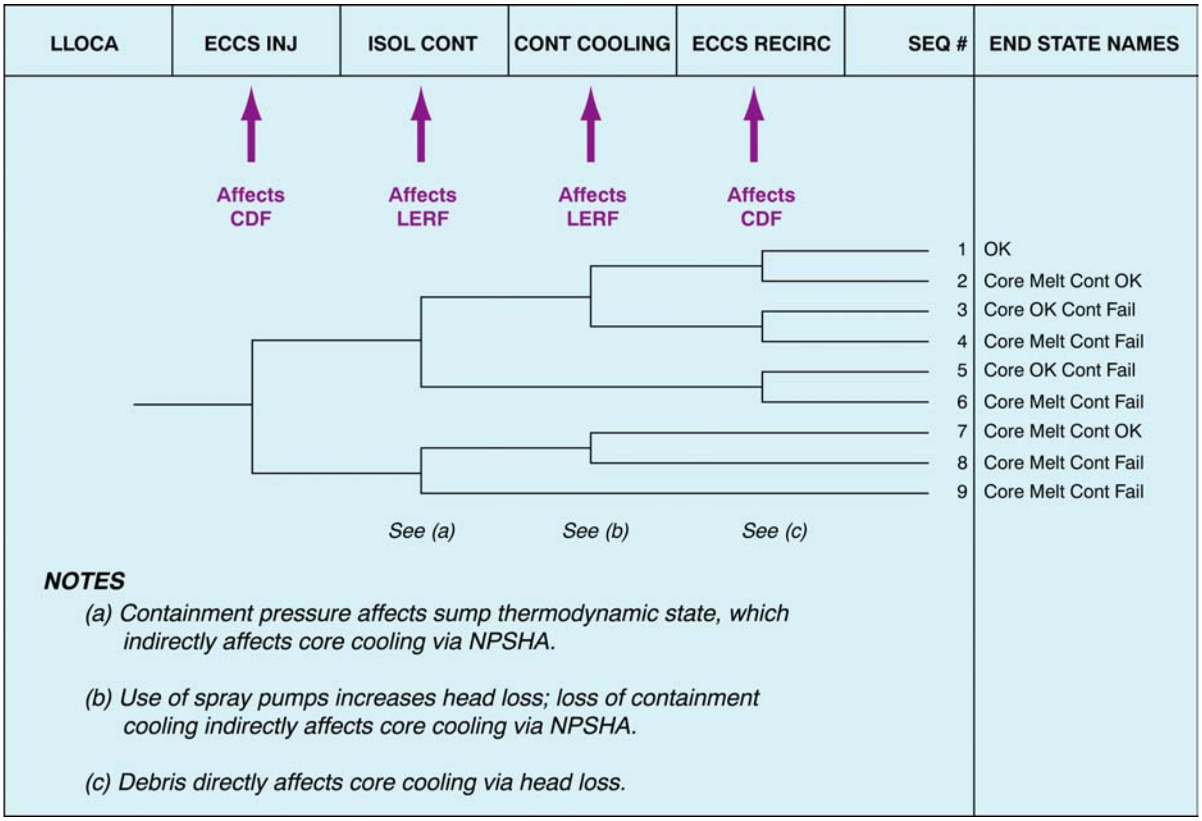

Fig. 2. CDF and LERF included in an event tree.

The event-tree structure defines the plant conditions for any particular accident sequence so that results from the studies of debris phenomena can be used to estimate a conditional probability of sump-recirculation failure. Such plant conditions include the number of pumps using the sump for core/containment cooling, the size and location of the break where fluid is released into containment, the time following the break when the sump is required, and so on. Figure 3 shows how an event explicitly addressing the effects of debris will be included in each event tree.

The event-tree structure also explicitly allows quantification of numerous accident sequences at the systems level. Each initiating event has a unique event tree that delineates all possible accident progressions as combinations of systems successes and failures. Event trees can be extended to the component level by modeling the success probability of each event with a fault tree. Analysis tools such as SAPHIRE automatically link the fault trees for the various events in a sequence. Fault trees may be needed in this study to quantify the success probability of some events for which there are no available industry data.

Possible strategies that operators might use to limit the severity of an accident, such as “feed and bleed” or recirculation-pump throttling, can be explicitly included in the event trees as shown in Fig. 4. Successful mitigation will reduce the likelihood of core damage. The availability of some strategies is highly plant-specific, so these events will be introduced parametrically to help judge their effects on the industry-wide risk of sump blockage.

All accident sequences can be quantified with both licensing-assumption and most-likely success probabilities as shown in Fig. 5. Contrary to what is shown in the figure for the purpose of an example, all events in the tree will be quantified by *either* “most likely” probabilities *or* licensing-basis probabilities for any given analysis.

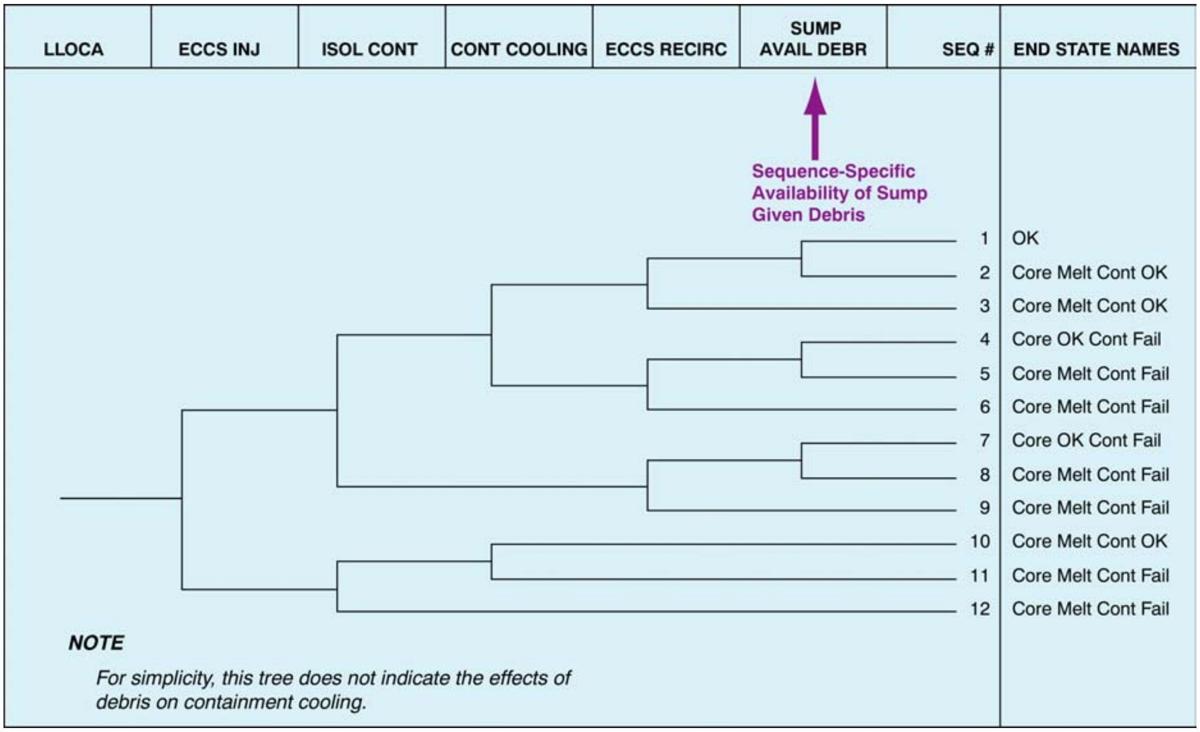

Fig. 3. Explicit inclusion of debris effects in an event tree.

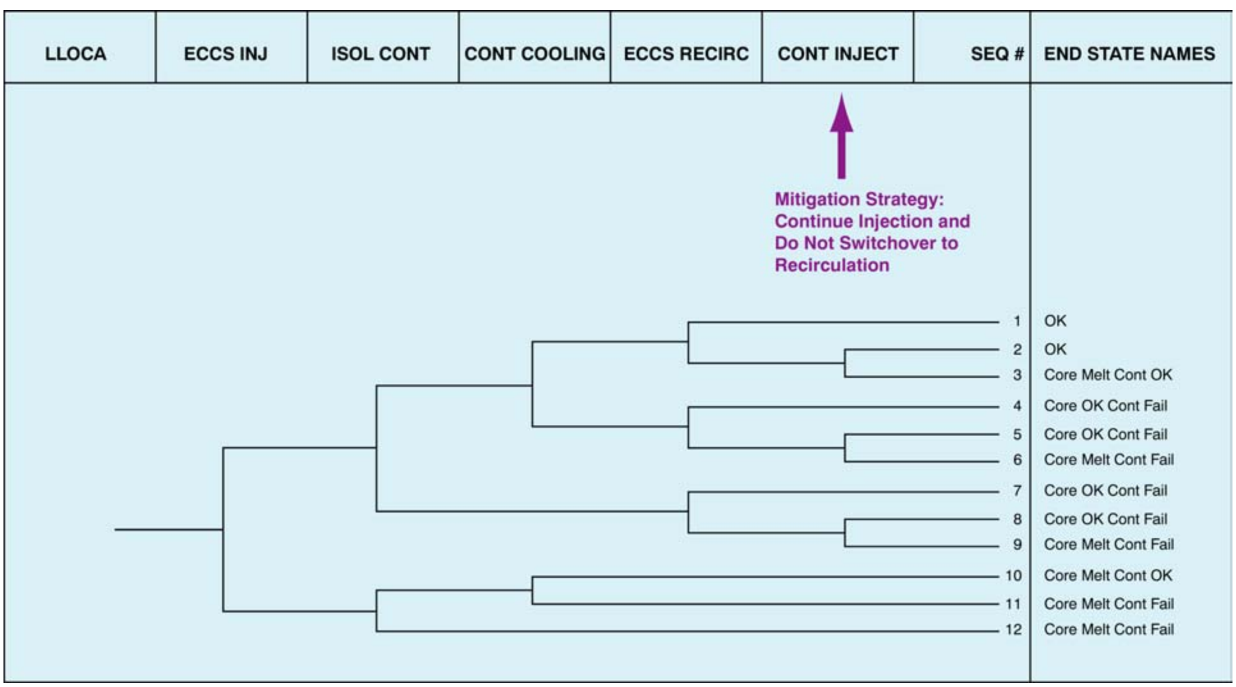

Fig. 4. Explicit consideration of possible mitigation strategies.

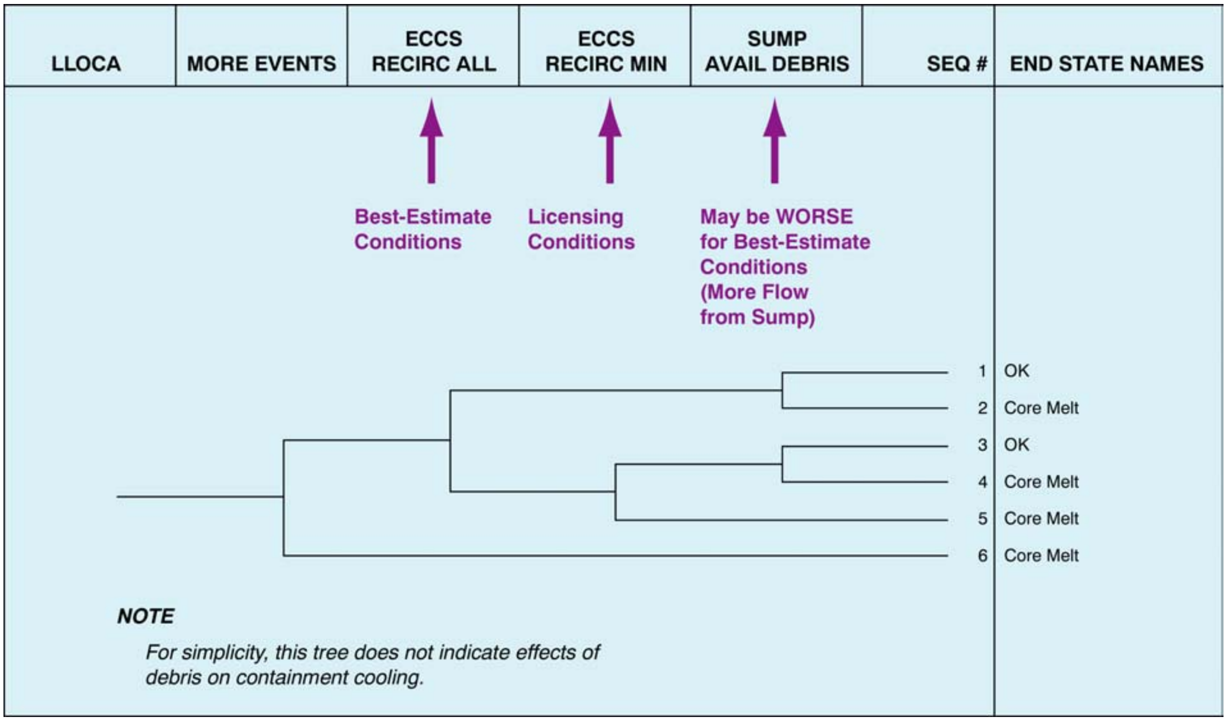

Fig. 5. Consideration of licensing assumptions and most likely plant response.

4.0. INTERFACE WITH DEBRIS PHENOMENOLOGY STUDIES

4.1. Inclusion of Debris Phenomena in Event Trees

Results from the debris phenomena studies will be used to estimate the conditional probability that recirculation from the sump is not available because of the effects of debris generated by the accident. The manner by which the risk model interfaces with the debris studies is described in this section.

Let $CP_{ECCS\ FAIL\ DEBRIS}$ denote the conditional probability that the sump is not available to provide the required recirculation capacity because of the presence of debris. Because debris transport mechanisms may depend on the particular plant conditions, $CP_{ECCS\ FAIL\ DEBRIS}$ is accident-sequence specific. The event tree for each initiating event delineates the possible accident sequences by including

- an initiating-event description including the annual frequency of occurrence,
- subsequent plant-system states and their success/failure probabilities, and
- an explicit event in the tree (SUMP AVAIL DEBRIS) to introduce debris effects.

All ECCS failure mechanisms that are not related to debris effects will be accounted for in a separate event called ECCS RECIRC because previous estimates of the failure probability for this event are available from other sources. When ECCS failure mechanisms are separated in this way, the influences of debris phenomena can be analyzed explicitly.

Figure 3 showed an event tree that includes the event SUMP AVAIL DEBRIS. The conditional probability assigned to the event SUMP AVAIL DEBRIS depends on the accident sequence and the associated debris phenomena. Note that

$$CP_{ECCS\ FAIL\ DEBRIS} = 1 - CP_{SUMP\ AVAIL\ DEBRIS}$$

for each branch in the tree. *If* an accident sequence is developed in sufficient detail that deterministic models can be applied to evaluate all debris generation and transport phenomena, *then* $CP_{ECCS\ FAIL\ DEBRIS}$ is either 0 or 1, depending on the value of NPSHA relative to the success criterion net positive suction head required (NPSHR); i.e.,

$$CP_{ECCS\ FAIL\ DEBRIS} = 0 \text{ if } NPSHA \geq NPSHR$$
$$CP_{ECCS\ FAIL\ DEBRIS} = 1 \text{ if } NPSHA < NPSHR.$$

Note that NPSHR can be defined either by licensing bases, which incorporate a safety margin, or by the minimum pressure head needed to run the ECCS pumps at the capacity required for the accident sequence. In this way, ECCS success criteria also can be defined in terms of both "most-likely" and licensing-basis plant response.

To develop an accident sequence in complete detail, the following conditions must be defined quantitatively.

1. Plant design characteristics (PDCs) that determine spatial locations of insulated pipes and the sump, concrete boundaries limiting LOCA-jet expansion, debris-transport paths, allowed mitigative actions determined by available equipment, etc.
2. Plant system conditions (PSCs) that define the number (and volume) of safety systems drawing from the sump, the status of containment sprays and containment integrity, etc.
3. Sump-state (SS) parameters like water depth, temperature and flow rates that determine NPSHA
4. All debris phenomena (DP) that affect debris generation at the location of a break, transport to the sump, and build-up on the screen

This set of information provides the interface between plant-system models that describe the status and requirements for emergency operation and the debris phenomenology models that describe the physics of the accident progression and the effect of debris on sump availability. Although the assignment of information into these four categories is somewhat arbitrary and interdependencies probably will be found, the process of itemizing necessary information ensures that the coupling between these two pieces of the risk analysis will be complete. In many respects, this interface is perfectly analogous to the definition of plant damage states that provide a transition between traditional Level 1 PRA, which investigates the severity of a reactor core breach, and Level 2 PRA, which propagates a small set of accident conditions to the point of environmental release.

PDCs are the important design features that affect the propagation of an initiating event into the various accident sequences that may follow. For example, at a specific plant, feed and bleed may be accomplished with either safety *or* relief valves, whereas at another plant, relief valves may be required. PDCs also provide some of the conditions under which debris phenomena are to be evaluated for specific accident sequences. For example, at some plants, the safety valves discharge into the pressurizer quench tank, and at other plants, they discharge directly into containment with the possibility of debris generation.

In addition, the physical design of the plant will always have an important influence on the outcomes of debris-generation and transport scenarios. For example, the presence of concrete "doghouses" may limit the expansion of a LOCA jet in the vicinity of a steam generator, and openings from steam-generator cavities will often dictate the path of water flow from a major break to a remote sump located in an outer annulus. The locations and types of insulation are also examples of PDCs that must be included in the physical plant description.

The following PDCs affect the NPSHA and NPSHR, which represent the ECCS performance metric and success criterion, respectively.

- Sump design (elevation, size, strainers, etc.)
- Pump design (elevation, type, NPSHR)
- Containment design (size, floor details)
- Size of water sources (ECCS injection, accumulators, RCS inventory)

Each accident sequence is defined by a specific combination of an initiating event and subsequent system failures and successes; PSCs are represented by that accident-sequence-specific set of combinations. The PSCs for a given accident sequence can affect the importance of the debris in causing loss of the sump. For example, the total number of pumps pulling from the sump (required to support ECCS and containment-spray recirculation) affects the

NPSHA for every pump, and the number of pumps in operation is specified by the PSCs for the applicable event-tree accident sequences. The following PSCs affect NPSHA and NPSHR.

- Initiating event (determines RCS conditions and containment pressure)
- Requirement to use ECCS (initiating event and subsequent system failures, e.g., transient with loss of feedwater requires ECCS for feed and bleed, and operator mitigative actions, e.g., continued injection)
- State of the ECCS (number of pumps, time to switchover to recirculation, high- or low-pressure pumps in sequence)
- Containment isolation successful or failed
- State of containment cooling systems (core spray on, number pumps, fan coolers on, number of coolers)

The SS is the physical state of the fluid in the sump, which affects the ability of the sump to function with debris present. The SS depends on the PDCs and the PSCs. The following SS considerations affect the NPSHA and NPSHR.

- Plant system conditions
- Sump conditions such as
  - amount of water in sump and
  - pressure and temperature (dependent on containment pressure and temperature)

Debris phenomena affect the likelihood that the sump is lost as a result of debris effects. The DP define the minimum set of information needed to describe the physical generation and transport of debris from the occurrence of a break at a specific location to potential build-up at the sump screen. In a generic sense, the DP can be thought of as particular values of the input parameters required by predictive debris generation and transport models that have been (or are being) developed to explain experimental observations of debris behavior. These models eventually may differ in complexity from simple engineering approximations of generated debris volume to detailed computational fluid dynamics (CFD) models of debris transport. The following DP parameters affect NPSHA and NPSHR.

- Initiating event (size of "break," location of break, discharge path to containment)
- Amount, type, and size distribution of debris source
- Transport of debris to and on containment floor
- Settling of debris in containment
- Effect of debris on head loss
- Other parameters (if necessary)

Factors affecting the ECCS performance metric NPSHA are summarized below.

Physical Property	**Important Conditions**
Sump/Pump Properties	
Thermodynamic state of sump (containment conditions)	SS
Sump size, pump elevation, head loss with no debris	PDCs
Sump water level	PSCs, PDCs
Debris Effects	
Head loss across strainer with debris	DP

Factors affecting the ECCS success criterion, NPSHR follow.

Physical Property	**Important Condition**
Pump design	PDCs
Flow rate through pump	PSCs
Pump Speed (not of concern for constant speed pumps)	PDCs
Water temperature (may not be significant)	SS

PDCs and the SS can be addressed using calculations from modeling tools such as RELAP and MELCOR. Both depend on the PSCs that are delineated explicitly in the event-tree structures. Therefore, the event trees will incorporate the PDCs and the PSCs from which the SS can be calculated. The resultant PDCs, PSCs, and SS provide the conditions for which the DP are to be evaluated for a given accident sequence. The DP effect on the given accident sequence will be calculated using phenomenological models developed in the concurrent debris investigation of the overall sump-blockage risk assessment.

Given sufficient details at each step, the basic procedure to quantify the failure of the sump for each specific accident sequence is as follows.

- Specify PDCs
- Calculate PSCs and SS
- Estimate DP
- Determine NPSHA and NPSHR

An issue of some importance is whether it is practical to develop event trees in sufficient detail to quantify $CP_{ECCS\ FAIL\ DEBRIS}$ as either 0 or 1. Recall that all input parameters required for deterministic debris-generation and transport models must be specified for a given scenario before a clear decision can be made regarding sump availability. It is argued in the following discussion that although it *is* practical to address PDCs, SS, and PSCs in detail on the event trees, it *is not* practical to address DP in sufficient detail on the event trees. Additional consideration must be given to the interface between the event-tree systems models and the DP phenomenology models.

The accident sequences developed in the event trees will include all of the details required to specify the PDCs and the PSCs. These parameters represent large-scale plant conditions that dictate major branches or decision points along the possible event sequences. The actions taken at each branch to change the plant status (whether by intent or by equipment failure) are discrete and, in most cases, binary events that are easily accommodated by the event-tree logic. At most, 10 to 12 branches will be needed to capture all plant configurations of interest during an accident. Even the numeric values associated with each plant state are limited to a few possible discrete values. For example, maximum recirculation flow rates will be set by the number of cooling systems that are operating in a given scenario.

By comparison, phenomenology models require the values of many continuous variables that are not divided easily into a manageable number of discrete bins. Factors that complicate specifying $CP_{ECCS\ FAIL\ DEBRIS}$ as either 0 or 1 for each accident sequence include the following.

- The fidelity of RELAP/MELCOR calculations affects the determination of the SS, which must be known to compare NPSHA and NPSHR.
- A given LOCA initiating event comprises a large number of different possible break locations, each with different debris-generation potential, and this affects the DP.
- There is uncertainty in the debris phenomena (volume, transport, settling, etc.) that affects the outcome of an accident sequence in terms of sump availability.

The SS results from RELAP/MELCOR calculations can be included either explicitly through additional events in the event-tree accident sequences or implicitly through the assignment of event-failure probabilities. However, the DP are too complicated to address in detail in the event trees. It is not feasible to develop accident sequences in sufficient detail to uniquely specify all debris phenomena; there are too many parameters with continuous ranges of possible values. Therefore, a composite approach will be used to estimate $CP_{ECCS\ FAIL\ DEBRIS}$ that is derived from a statistical combination of parameters that are important for DP. This statistical combination is discussed below.

In summary, the accident sequences on the event trees will be developed in sufficient detail to uniquely specify all parameters needed to calculate $CP_{ECCS\ FAIL\ DEBRIS}$, except for the parameters associated with DP. In other words, only the parameters associated with PDCs, PSCs, and SS will be handled in the event-tree structure. For each accident sequence, DP effects will be calculated using phenomenology submodels, and $CP_{ECCS\ FAIL\ DEBRIS}$ will be estimated as a composite value derived from a statistical combination of important parameters. There are two potential complications with this approach.

1. Dependent effects between DP and plant status may complicate segregation of the accident sequences into separate pieces, and the approach may require refinements as such effects are encountered.
2. The core/containment interface is inherently complicated. Choices for addressing it include (a) model in detail, (b) model with simplifying assumptions, or (c) use conservative assumptions (e.g., Regulatory Guide 1.1).

Item 1 is complicated because there is no general mathematical approach for describing dependencies in an event-tree structure. Complicated dependent effects will be handled on a case-by-case basis. Item 2 is complicated because a rigorous solution of the core/containment response requires a coupled analysis.

4.2. Quantification of Debris Phenomena as a Composite Value

For each accident sequence, there is a defined "hole" size for release of fluid into containment. This size is largely determined by the industry-standard definitions of large, medium, and small LOCA events. Other important variables will be specified by a Break Set (BS). The BS includes {break size, location, pipe size, reactor system, jet geometry, orientation of a directional jet}. Important considerations that are addressed by parameters in the BS include the following.

- Break location. Not all locations have the same frequency of break; e.g., welds, bends, etc.; and insulation types will not be distributed uniformly in containment.
- Pipe size. A total break in a smaller pipe will not have the same depressurization behavior as the same size hole in the sidewall of a larger pipe.
- Reactor system. Some systems may deserve credit for LBB; others may not.

The variables affecting generation of insulation debris and subsequent transport to the sump given a specific BS will be specified by a Debris Set (DS). The DS includes {volume and type generated, reactor system mounted on, initial spatial distribution, volume and type transported, head loss created}. Many background details such as insulation damage pressures and insulation type, thickness, and installation location will be treated as plant configuration information. For example, it may be of interest to replace the specific insulation types of a volunteer plant with another combination that is prevalent in the industry.

Deterministic models will not be available for all steps of the generation and transport analysis. Therefore, many parameters like break location and possibly jet orientation will be sampled randomly from the total range of possibilities. Stochastic evaluation of uncertain parameters implies that a large number of such evaluations may be required, i.e., the BS and DS may have many elements. If each set is imagined as a rectangular matrix, then the values of any row from BS and any row from DS completely define the conditions for a single postulated accident.

4.2.1. Calculation Process. For each accident sequence (AS), there will be a specific $CP_{ECCS\ FAIL\ DEBRIS}(AS)$. Let BS_i denote the i^{th} unique Break Set and DS_k denote the k^{th} unique Debris Set. DS_k is dependent on BS_i. To account for all Break Sets, $CP_{ECCS\ FAIL\ DEBRIS}(AS)$ is a weighted combination of a set of conditional probabilities $P_{Fail\ Sump\ Debris}(AS, BS_i)$ over all i break sets. To account for all Debris Sets, $P_{Fail\ Sump\ Debris}(AS, BS_i)$ is in turn a weighted sum of a set of conditional probabilities $P_{Fail\ Sump\ Specific\ Debris\ Set}(AS, BS_i, DS_{i,k})$ over all k debris sets. Each $P_{Fail\ Sump\ Specific\ Debris\ Set}(AS, BS_i, DS_{i,k})$ has a value of either 0 or 1.

$$CP_{ECCS\ FAIL\ DEBRIS} = \sum_{i\ Break\ Sets} W_i\, P_{FAIL\ SUMP\ DEBRIS}(AS, BS_i)$$

where W_i is a weighting factor; the sum of W_i over all i is 1.0.

$$P_{FAIL\ SUMP\ DEBRIS}(AS, BS_i) = \sum_{k\ Debris\ Sets} W_{i,k}\, P_{FAIL\ SUMP\ SPECIFIC\ DEBRIS\ SET}(AS, BS_i, DS_{i,k})$$

where $W_{i,k}$ is a weighting factor and where $P_{Fail\ Sump\ Specific\ Debris\ Set}$ $(AS, BS_i, DS_{i,k}) = 0$ or 1. The sum of $W_{i,k}$ over all k is W_i.

The use of weighting factors based on the likelihood of occurrence for each element of the BS and DS will produce the arithmetic mean value of the distribution of possible binomial 0/1 outcomes. This is consistent with the selections that will be made for all other system failure probabilities throughout the event trees. Although complete probability distributions can sometimes be defined for each branch, only the mean values propagate multiplicatively through the tree to provide mean values of the endstate frequencies. More complex techniques for sampling branch probabilities will not be used in this analysis.

Note that the notation has been generalized here to account for the possibility of multiple DS for each BS, but the simulations may be run with only a single DS outcome for each element of the break set. In this case, the above equation collapses to a single summation for all practical purposes.

4.2.2. Simple Discussion of the Calculation Process. The previous section provided the mathematical approach for assigning a value to $CP_{ECCS\ FAIL\ DEBRIS}$ for a given accident sequence using the DP. This section provides a simple physical explanation of the process.

The event-tree structure will be developed sufficiently to uniquely specify the PDCs, PSCs, and SS for each accident sequence on each event tree. It is neither practical nor necessary to delineate all the DP on the event trees. It is not practical because there may be many thousands of combinations of values for the BS and DS parameters discussed previously. It is not necessary because the event tree is defined at a systems level. Just as the event tree does not delineate all the ways that a system can fail, it should not delineate all possible debris phenomena. By a similar analogy, because the mean failure probability of a system is calculated from a statistical combination of failures of constituent components, the availability of recirculation from the sump should be calculated from a statistical combination of DP.

Consider a specific event sequence on a LLOCA event tree. The overall frequency of a LLOCA is the frequency of the initiating event (assume 5E-4/yr). However, the effect of the LOCA on generating debris depends on the type of break (double-ended guillotine or crack), the exact size of the break in the LLOCA range, the proximity of the break to insulation, the type of insulation, the location of the affected insulation in containment, etc. Therefore, the overall break frequency of 5E-4/yr must be distributed over numerous specific breaks whose individual frequencies statistically sum to 5E-4/yr. Each individual break must be evaluated to determine whether the resultant debris causes NPSHA to be less than NPSHR or not because different breaks will have different DP.

The weighting factors $W_{i,k}$ are the fractions of the overall initiating-event frequency that result from the specific accident conditions defined in the break and debris sets. For example, if all large breaks are considered equally likely and there are 1000 breaks, the weighting factor is the same for each break, namely, 0.001. The initiating event defines the overall frequency; therefore, the product of the initiating-event frequency and the weighting factor for a constituent break is the frequency of that break (5E-7/yr/break for each constituent LLOCA break if each of 1000 constituent breaks is equally likely). If it is desired to address factors that cause the likelihoods of various breaks to differ, such as the effect of welds and pipe bends, then the weighting factor can be defined nonuniformly among the constituent breaks. At the present time, this possibility is under evaluation. The sum of all weighting factors for a given event sequence must always equal 1.0.

For a given break, the probability that the sump is lost because of debris effects is 0 or 1 depending on the DP for that specific break. The assignment of the probability that the sump is lost for each break will be based on phenomenological evaluations. For 1000 constituent breaks, there will be a set of 1000 values (each 0 or 1) that can be weighted by their relative likelihoods of occurrence (the weighting factors) to obtain the overall probability that the sump is lost because of debris in the accident sequence of concern. This overall probability is $CP_{ECCS\ FAIL\ DEBRIS}$ for a given accident sequence. Separate $CP_{ECCS\ FAIL\ DEBRIS}$ will be calculated in the same manner for each accident sequence in each event tree.

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