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PRA Procedures and Uncertainty for PTS Analysis

Office of Nuclear Regulatory Research

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ABSTRACT

This report supplements NUREG-1806, "Technical Basis for Revision of the Pressurized Thermal Shock (PTS) Screening Limit in the PTS Rule (10CFR50.61): Summary Report," with additional information regarding the Probabilistic Risk Assessment (PRA) and Human Reliability Analysis (HRA) portions of the PTS analyses presented in that report, including the use of realistic input values and models and an explicit treatment of uncertainties. Best estimate equipment failure values are used throughout based on generic nuclear industry data, or, in cases where it's available, on plant-specific data. Parameters related to human performance are based on plant specific review of procedures and training, observation of plant personnel responding to PTS-related sequences on their simulator, and performance data from actual plant operations.

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FOREWORD

The reactor pressure vessel is exposed to neutron radiation during normal operation. Over time, the vessel steel becomes progressively more brittle in the region adjacent to the core. If a vessel had a preexisting flaw of critical size and certain severe system transients occurred, this flaw could propagate rapidly through the vessel, resulting in a through-wall crack. The severe transients of concern, known as pressurized thermal shock (PTS), are characterized by rapid cooling (i.e., thermal shock) of the internal reactor pressure vessel surface that may be combined with repressurization. The simultaneous occurrence of critical-size flaws, embrittled vessel, and a severe PTS transient is a very low probability event. The current study shows that U.S. pressurized-water reactors do not approach the levels of embrittlement to make them susceptible to PTS failure, even during extended operation well beyond the original 40-year design life.

Advancements in our understanding and knowledge of materials behavior, our ability to realistically model plant systems and operational characteristics, and our ability to better evaluate PTS transients to estimate loads on vessel walls have shown that earlier analyses, performed some 20 years ago as part of the development of the PTS rule, were overly conservative, based on the tools available at the time. Consistent with the NRC's Strategic Plan to use best-estimate analyses combined with uncertainty assessments to resolve safety-related issues, the NRC's Office of Nuclear Regulatory Research undertook a project in 1999 to develop a technical basis to support a risk-informed revision of the existing PTS Rule, set forth in Title 10, Section 50.61, of the Code of Federal Regulations (10 CFR 50.61).

Two central features of the current research approach were a focus on the use of realistic input values and models and an explicit treatment of uncertainties (using currently available uncertainty analysis tools and techniques). This approach improved significantly upon that employed in the past to establish the existing 10 CFR 50.61 embrittlement limits. The previous approach included unquantified conservatisms in many aspects of the analysis, and uncertainties were treated implicitly by incorporating them into the models.

This report is one of a series of 21 reports that provide the technical basis that the staff will consider in a potential revision of 10 CFR 50.61. The risk from PTS was determined from the integrated results of the Fifth Version of the Reactor Excursion Leak Analysis Program (RELAP5) thermal-hydraulic analyses, fracture mechanics analyses, and probabilistic risk assessment. This report documents the Probabilistic Risk Assessment (PRA) and Human Reliability Analysis (HRA) portions of the PTS study.

Brian W. Sheron, Director
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A key final product of the PTS re-analysis project was the estimation of thru-wall crack frequencies (TWCFs) associated with severe overcooling scenarios using the probabilistic fracture mechanics code FAVOR. The PRA portion of the re-analysis project had three primary purposes in the derivation of this final product:

1. Define the overcooling scenarios (sequences) with the potential for being PTS challenges. This resulted in definition of the overcooling sequences, is in the form of the event trees constructed by the PRA analysts for each of the three plant PTS analyses.
2. Direct the TH analysis as to the specific sequences to be modeled so as to obtain plant TH response information to be forwarded to the PFM analysts.
3. Estimate the frequencies, including uncertainties, for those overcooling sequences potentially important to the PTS results and provide that information to the PFM analysts. These estimates were provided to the PFM analysts by the PRA analysts for those overcooling "case" bins potentially important to the PTS results. This information was provided in the form of electronic files containing a "case" bin identifier and statistical frequency information associated with that bin. These bin frequencies correspond to the "case" sequences modeled by the TH analysts and represent the combined frequencies of all the event tree sequences incorporated into each bin. The statistical frequency information along with the TH information representing each bin were then used by the PFM analysts to estimate the TWCFs.

A multi-step approach was followed to produce the PRA products for the PTS re-analysis project. These steps included the following:

Step 1: Collect information
Step 2: Identify the scope and features of the PRA model
Step 3: Construct the PRA models
Step 4: Quantify and bin the PRA modeled sequences
Step 5: Revise PRA models and quantification
Step 6: Perform uncertainty analysis
Step 7: Incorporate uncertainty and finalize results

These steps both define the sequences of events that may lead to PTS (for input to the TH model) and estimate the frequencies with which these sequences are expected to occur (for combination with the PFM results–e.g., conditional probability of initiation (CPI) and conditional probability of failure (CPF)–to calculate the yearly frequency of through wall cracking). This report provides a detailed description of each of these seven steps.

ABBREVIATIONS

AC	Alternating current
ADVs	Atmospheric dump valves
AFW	Auxiliary feedwater
ATWS	Anticipated transient without scram
CPF	Conditional probability of failure
CPI	Conditional probability of initiation
DC	Direct current
EFW	Emergency feedwater
HEPs	Human error probabilities
HRA	Human reliability analysis
HZP	Hot zero power
IPTS	Integrated Pressurized Thermal Shock Studies
LER	Licensee event report
LOCA	Loss of coolant accident
MFW	Main feedwater
MSIVs	Main steam isolation valves
PFM	Probabilistic fracture mechanics
PORVs	Power-operated relief valves
PRA	Probabilistic risk assessment
PTS	Pressurized thermal shock
PWRs	Pressurized water reactors
RCPs	Reactor coolant pumps
RCS	Reactor coolant system
SG	Steam generator
SGTR	Steam generator tube rupture
SRVs	Safety relief valve
SSRVs	Secondary steam relief valves
TH	Thermal-hydraulic
TWCFs	Through-wall crack frequencies
UMD	University of Maryland

1. INTRODUCTION

The NRC Office of Nuclear Regulatory Research started a study in 1999 to develop the technical basis for a risk-informed revision of the PTS Rule which would relax unnecessary conservatisms in the present PTS rule (10CFR50.61) without compromising safety. That study and its results are summarized in NUREG-1806, "Technical Basis for Revision of the Pressurized Thermal Shock (PTS) Screening Limit in the PTS Rule (10CFR50.61): Summary Report."

This report supplements NUREG-1806 with additional information regarding the Probabilistic Risk Assessment (PRA) and Human Reliability Analysis (HRA) portions of the PTS study, including the use of realistic input values and models and an explicit treatment of uncertainties. As depicted in Figure 1, the PTS re-analysis project was a closely integrated effort among three primary technical disciplines:

1. PRA (including HRA),
2. Thermal-hydraulic (TH) modeling, and
3. Probabilistic fracture mechanics (PFM).

As such, while this report focuses on the PRA and HRA (hereafter referred to as PRA unless specifically dealing with HRA) aspects of the re-analysis, important interfaces with the other technical disciplines are noted and cannot be completely separated from what was done in the PRA portion of the PTS re-analysis project.

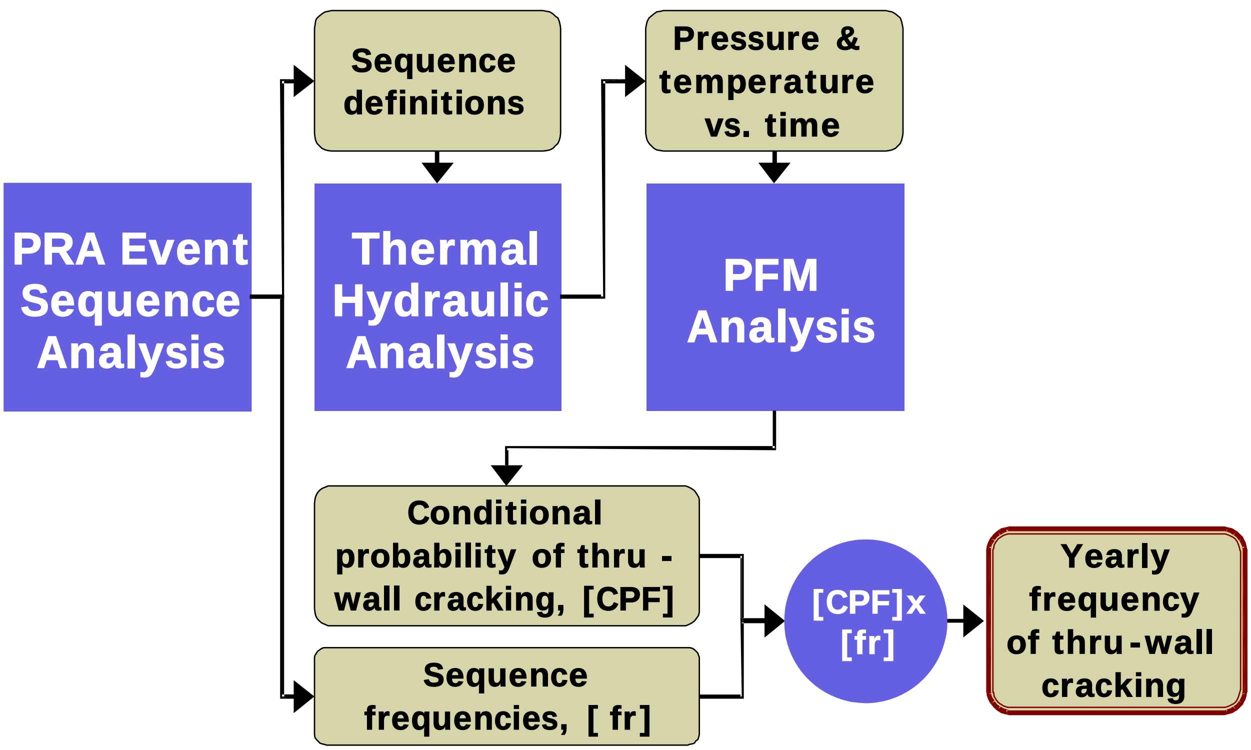

Figure 1. Integrated technical analyses comprising the PTS re-analysis project.

2. PURPOSE AND PRODUCTS

A key final product of the PTS re-analysis project was the estimation of thru-wall crack frequencies (TWCFs) associated with severe overcooling scenarios. The PRA portion of the re-analysis project had three primary purposes in the derivation of this final product:

1. Define the overcooling scenarios (sequences) with the potential for being PTS challenges.

2. Direct the TH analysis as to the specific sequences to be modeled so as to obtain plant TH response information to be forwarded to the PFM analysts.

3. Estimate the frequencies, including uncertainties, for those overcooling sequences potentially important to the PTS results and provide that information to the PFM analysts.

In meeting the above purposes, the process followed by the PRA analysts was iterative in nature. These iterations were the result of additional information becoming available from the other disciplines as the analyses evolved, as well as due to feedback from the licensees participating in the three plant analyses (Oconee Unit 1, Beaver Valley Unit 1, and Palisades Unit 1).

For each purpose above, a specific product was produced. The first product, definition of the overcooling sequences, is in the form of the event trees constructed by the PRA analysts for each of the three plant PTS analyses. Event tree construction is a well-known and well-established PRA modeling tool that has been used in identifying and analyzing core damage scenarios such as in the Individual Plant Examination (IPE) program. In this case, the same tool was used to identify and model overcooling sequences rather than core damage sequences that could occur as a result of under-cooling events. The sequences depicted by the PTS event trees represent those combinations of initiating events that disrupt normal plant operation (e.g., turbine trip) and subsequent plant equipment and operator responses that are included in each plant model to represent overcooling sequences with the potential to be a PTS challenge.

The second product, direction by the PRA analysts to the TH analysts as to specific sequences to be modeled in their phase of the overall PTS analyses, was provided in the form of written and vocal communications among the analysts. Each TH modeled sequence was assigned a “case” number for identification purposes. For a given plant analysis, each TH “case” is a scenario that broadly represents many possible sequences on the event trees for that plant whose characteristics are similar enough that the sequences can be collectively represented by a single TH sequence (case). The TH analysts modeled each case to derive the time histories for reactor coolant pressure, reactor vessel downcomer temperature, vessel wall heat transfer characteristics, and other parameters important to defining the plant TH response during each case. This response information was subsequently provided to the PFM analysts to determine the vessel wall response (i.e, crack initiation and propagation) for the TH conditions. The modeling of multiple event tree sequences by a smaller number of “case” sequences involved a manual *binning* process that is summarized later in more detail.

The third product, sequence frequencies including uncertainties, was provided to the PFM analysts by the PRA analysts for those overcooling “case” bins potentially important to the PTS results. This information was provided in the form of electronic files containing a “case” bin identifier and statistical frequency information associated with that bin. These bin frequencies correspond to the “case” sequences modeled by the TH analysts and represent the combined frequencies of all the event tree sequences incorporated into each bin. The statistical frequency information along with the TH information representing each bin were then used by the PFM analysts to estimate the TWCFs [Dickson].

3. PTS PRA METHODOLOGICAL APPROACH

A multi-step approach was followed to produce the PRA products for the PTS re-analysis project. Figure 2 depicts the steps followed both to define the sequences of events that may lead to PTS (for input to the TH model) and to estimate the frequencies with which these sequences are expected to occur (for combination with the PFM results–e.g., conditional probability of initiation (CPI) and conditional probability of failure (CPF)–to calculate the yearly frequency of through wall cracking). Although the approach is illustrated in a serial fashion, its implementation involved multiple iterative passes through the various steps as the analyses and the mathematical representation of each plant evolved. In the following sections, seven steps that together comprise the PRA analysis are described. These seven steps include:

Step 1: Collect information (Section 3.1)
Step 2: Identify the scope and features of the PRA model (Section 3.2)
Step 3: Construct the PRA models (Section 3.3)
Step 4: Quantify and bin the PRA modeled sequences (Section 3.4)
Step 5: Revise PRA models and quantification (Section 3.5)
Step 6: Perform uncertainty analysis (Section 3.6)
Step 7: Incorporate uncertainty and finalize results (Section 3.7)

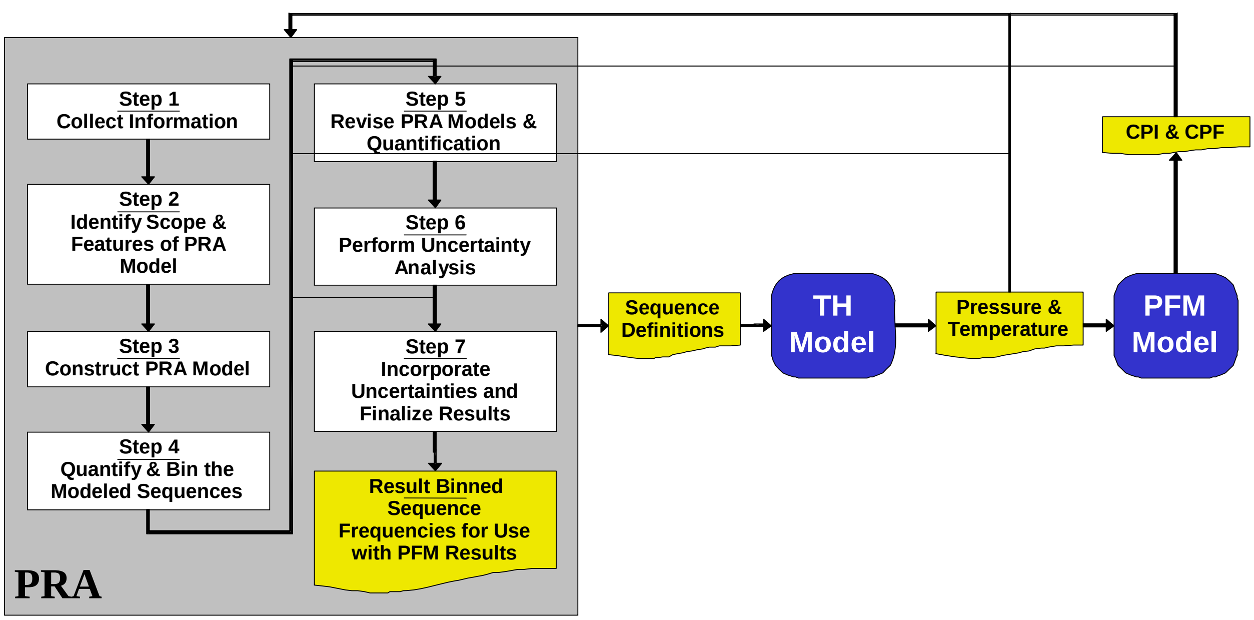

Figure 2. Diagrammatic representation of PRA approach.

3. PTS PRA Methodological Approach

The reader should recognize that the PRA models described in this report consider *only* events internal to the operating plant (stuck open valves, pipe breaks, etc.) as possible PTS precursors[1]. A scoping study aimed at assessing the frequency and the consequences of external initiating events (e.g., fires, floods, etc.) is detailed in a separate document [Kolaczkowski 04a].

3.1 Step 1: Collect Information

During the initial phase of the PTS project, significant resources were expended to collect information regarding PTS in general and each plant in particular. General information gathering activities included:

- a review of the basis for the current PTS rule [10CFR50.61], and
- a licensee event report (LER) search for the years 1980 through 2000 to gain an understanding of the frequency and severity of real overcooling events [INEEL 00a].

Plant specific information sources included the PRA analyses performed during the 1980s in support of the Integrated Pressurized Thermal Shock (IPTS) studies and the current PTS rule [ORNL 85a, 85b, 86], as well as plant-specific design and operational information. Familiarity with all of this information provided the bases upon which the PRA analysis of each plant was conducted.

3.1.1 Generic Information

3.1.1.1 LER Review

A total of 128 events were identified from the LER review, demonstrating that overcooling events, or at least their pre-cursors, do occur from time-to-time. These events are dominated by failure to properly control or throttle secondary side feed, a pre-cursor that leads to relatively minor over-cooling. Still, a few events have been associated with actual or potential loss of portions of secondary pressure control. These events predominantly involve equipment failures in the main feedwater, feed and steam control, and main steam systems. The results of the LER review also demonstrate that both active and passive (i.e., latent) human errors play a role as many of the equipment failures were caused by improper maintenance or testing. Additionally, equipment in non-normal configurations can be an aggravating factor because contributing equipment faults have occurred that operators must identify and compensate for to prevent over-cooling.

3.1.1.2 Initiator Frequency and Probability Date

Initiator frequency and failure probability data are needed for initiating events, systems, and components as input to the PRA model. Since the goal of the PTS re-analysis project was to provide a PTS risk perspective for the operating fleet of pressurized water reactors (PWRs), it was judged appropriate to apply industry-wide PWR data for initiator frequencies and equipment failure probabilities in the plant-specific analyses. Hence, while the PRA model structure and the operational considerations it represented were based on plant-specific information, initiator frequencies and equipment failure probability data were generally based on industry-wide experience.

Generic PWR data were obtained from two main sources. The first source, NUREG/CR-5750 [INEEL

[1]Internal flooding events were *not* considered in this analysis; however, they were examined in the external events scoping study.

99], summarizes industry-wide initiator experience for the years 1987 through 1995 along with failure probabilities for selected components. This information was updated twice. The first update was performed in an unpublished (at the time) addendum to NUREG/CR-5750 [INEEL 00b] that extended the experience base through 1998. The second update dealt with loss-of-coolant initiators and was based on NRC staff input intended to account for time dependent material aging mechanisms not included in the experiential data [NRC LTR 02][2]. The second source, NUREG/CR-5500, [INEEL] summarizes industry-wide experience for selected systems.

3.1.2 Specific Information

3.1.2.1 Previous PTS-PRA Analyses

Review of the PRA analyses performed in support of the IPTS studies and the current PTS rule was another important input to the analyses. Of particular relevance were NUREG/CR-3770 [ORNL 86] and WCAP-15156 [Westinghouse 99] (a more recent 1999 study) since these are past analyses of two of the plants covered in this work, Oconee and Beaver Valley respectively. Information in NUREG/CR-4183 [ORNL 85b] concerning H.B. Robinson and NUREG/CR-4022 [ORNL 85a] concerning Calvert Cliffs plant was also considered since these documents provided additional perspectives and analytical considerations useful to this work.

3.1.2.2 Plant-Specific Information

At the outset of each plant-specific analysis, a letter was sent to the licensee requesting information pertaining to plant design, procedures, training, and other aspects of plant operation relevant to building a PRA model for analyzing PTS. Information provided in response to these letters was supplemented by information gained during plant visits and by ongoing interactions (vocal, written, and e-mail exchanges) with each licensee as the analyses evolved. In total, plant-specific information was derived from the following sources:

- Summaries of any recent past actual overcooling events
- Current PRA model and writeups
- Final Safety Analysis Report sections
- Piping and Instrument Diagrams and electrical drawings
- Emergency and Abnormal Operating Procedures
- Miscellaneous system design basis information and related material
- PTS-relevant training material
- Operational aspects associated with hot shutdown conditions

[2] Generic initiator frequency information (as described in Section 3.1.1.2) was used for Oconee Unit 1 and Beaver Valley Unit 1, whereas the plant-specific PRA conducted by Consumers' Energy personnel (for Palisades Unit 1) ostensibly incorporated plant-specific initiator frequency information.

- Observation of multiple simulator exercises at each plant involving overcooling events that were set-up and run as part of a collaborative effort between each licensee and the NRC contractor PRA analysts

- Periodic interactions with the licensees regarding modeling details as each analysis evolved

- Feedback from each licensee as interim results from the analyses became available.

3.2 Step 2: Identify the Scope and Features of the PRA Model

The format, structure, and details considered in the current analyses draw considerably from the earlier PRA analyses of PTS. Aside from recognition of the results and the reasons for the results from these past analyses, limitations and conservatism associated with the past studies were identified and, to the greatest extent possible, alleviated. Other improvements were adopted with the intent of increasing both the accuracy and comprehensiveness of the PRA representation of the plants. Table 1 summarizes the differences between the current PRA and that used to support the current PTS rule. These differences fall into the following three major categories:

1. Greater refinement and detail in the current PRA

2. More realistic treatment of operator actions in the current PRA

3. Use of the latest available data on initiating event frequencies and equipment failure probabilities in the current PRA.

As noted in the table, since these improvements were made with the intent of increasing both the accuracy and comprehensiveness of the PRA representation of the plants, they neither systematically increase nor reduce the estimated risk from PTS.

In addition to identifying the areas for improvement of the PRA models that are noted in Table 1, review of past PRA analysis of PTS provided information in four other areas:

1. Identifying the types of sequences that needed to be included in the PRA
2. Identifying what types of initiating events should be included
3. Identifying what functions and equipment status needed to be included, and
4. Identifying what human actions needed to be considered.

The following four sub-sections describe the general features of the PRA models in each area. These features were established by a team approach involving analysts skilled in both system/sequence considerations and HRA considerations. Thus, the process for building PRA models involved integrated consideration of both system/sequence and human reliability factors.

Table 1. Comparison of PRA analyses used in this study with the PRA analyses that supported 10CFR50.61.

Difference Between Current PRA Analyses and the PRA Analyses that Supported 10CFR50.61			Effect on Calculated Risk	Comments
1	Refinement of / Detail Considered by the Analysis	Slight expansion of the types of sequences and initiators considered	Increase	
2		Slight expansion of support systems both as initiators and as dependencies affecting equipment response	Increase	
3		Less gross binning of TH sequences because there are more "cases" into which to bin individual TH runs	Reduce	Current work features 50-100 cases per plant whereas previous studies only considered about a dozen cases (e.g., small steamline breaks and the opening of 1-2 secondary valves were previously binned with a large guillotine steamline break, thereby treating the cooling effects of the smaller scenarios much too conservatively).
4		External initiating events considered as potential PTS pre-cursors	Increase	See [Kolaczkowski 04a].
5	Treatment of Operator Actions	Credit for operator actions is based on detailed consideration of numerous contextual factors associated with the modeled sequences, on multiple simulator observations at each plant, on the latest procedures and relevant training, and on numerous discussions with operating and training staffs. Detrimental acts of commission are also considered based on these same inputs, including procedural steps that call for operator actions that can exacerbate overcooling in certain situations.	Both Increase and Reduce	
6		A greater number of discrete operator action times are considered.	Reduce	Previous studies considered success or failure of operator action generally at 1 time after the start of the event. Currently, we consider up to 3 discrete times for operator action.
7	Use of New Data	Includes the latest industry-wide (and some plant-specific) data for initiating event frequencies, equipment failure probabilities, and common-cause considerations.	Reduce	Largest factor is the significant drop in the initiator frequencies as a result of the decrease in scram rates resulting from institutional programs executed in the ‘80s and ‘90s.

3.2.1 Types of sequences

The following list details the types of sequences included in the PRA models:

- overcooling scenarios,
  - at full/nominal power operation
  - at hot shutdown conditions

- loss of reactor coolant system (RCS) pressure scenarios,

- virtually sustained RCS pressure scenarios (i.e., scenarios where RCS pressure initially decreases, necessitating start of high pressure injection to restore pressure),

- late repressurization scenarios, and

- scenarios that provide immediate overcooling as well as those that begin as loss of cooling scenarios (i.e., under-cooling) and subsequently become overcooling scenarios.

Two types of scenarios commonly modeled in PRAs are not included in the current PTS analyses:

1. anticipated transients without scram (ATWS) scenarios, and
2. interfacing system loss-of-coolant accident (ISLOCA) scenarios.

Sequences resulting from such scenarios were not included based on the following considerations. First, ATWS events generally initially begin as a severe under-cooling event (i.e., there is too much power for the heat removal capability) and would likely involve other failures to achieve an overcooling situation even if it were possible to do so. While ISLOCAs, like the loss of coolant accidents (LOCAs) modeled in the PTS study, could involve overcooling from the start of the event, significant ISLOCAs are often assumed to fail mitigating equipment in PRAs which ultimately causes an under-cooling event and core damage. Second, with typical ATWS and sizeable (not just small leaks) ISLOCA frequency estimates in the E-5/yr to E-6/yr or even lower range and with the need for other failures to occur to possibly cause a continuing and serious overcooling situation, sequences involving ATWS or ISLOCAs should not be significant contributors to PTS risk. This is because the other modeled scenarios likely to be significant contributors to PTS risk have initiator frequencies commonly in the 1/yr to E-3/yr range, including other LOCAs that are already modeled in the PTS study.

3.2.2 Initiating Events

The following internal initiating events were included in the PRA models:

- Small-, medium-, and large-break LOCAs;
- Transients commonly modeled in PRA analyses, including:
  - Reactor-turbine trip,
  - Loss of main feedwater,
  - Loss of main condenser,
  - Loss of offsite power (including station blackout),
  - Loss of support systems such as AC or DC buses,
  - Loss of instrument air, and
  - Loss of various cooling water systems;
- Steam generator tube rupture (SGTR); and
- Small and large steamline breaks with and without subsequent isolation.

3.2.3 Functional/Equipment Considerations

The event trees in the PRA models that depict potential overcooling sequences are based on the status and interactions of four plant functions and associated plant equipment. Figure 3 presents a function-level event tree depicting the four functions and resultant general types of sequences treated in the PRA models. Each plant analysis features much more detailed event trees constructed at the initiator and equipment response level that incorporate the plant specific design and operational features. These four functions (i.e., primary integrity, secondary pressure, secondary feed, and primary flow / pressure) are important to treat in the PTS analyses for the following reasons:

- Primary integrity: The status of this function influences the potential RCS pressure, which in turn influences the rate of cooldown (in some situations), the injection source capability, and the incoming and outgoing flowrates. All of these factors influence the vessel downcomer temperature.

- Secondary pressure: The status of this function influences the pressure and temperature in the RCS, since the RCS and the secondary side of the plant are thermal-hydraulically coupled in most scenarios. For example, a rapid drop in secondary pressure can cause rapid cooling of the RCS, affecting both the downcomer temperature and, potentially, the RCS pressure (depending on subsequent RCS injection flow and heat removal).

- Secondary feed: The status of this function influences the pressure and temperature in the RCS, since the RCS and the secondary side of the plant are thermal-hydraulically coupled in most scenarios. For example, overfeed can contribute to enhanced cooling of the RCS, affecting both the downcomer temperature and, potentially, the RCS pressure (depending on subsequent RCS injection flow and heat removal).

- Primary pressure/flow: The status of this combination of conditions influences the RCS pressure and flow conditions (forced flow or natural circulation) during the overcooling event as well as the nature of the injection that can add cooling to the vessel wall. The flow characteristics either exacerbate or mitigate flow stagnation which can also affect the downcomer temperature.

In the plant-specific event trees, the status of equipment relevant to each function is modeled. This means that for each plant, the status of equipment relevant to each function is identified and included in the sequence modeling. For illustrative purposes, the following list summarizes the equipment associated with each function in the PRA models.

- Primary integrity: Status of pipe breaks, pressurizer power-operated relief valves (PORVs) and associated block valves, pressurizer safety relief valves (SRVs), and pressurizer heaters and spray considerations where appropriate.

- Secondary pressure: Status of steamline breaks, main steam isolation valves (MSIVs) and associated non-return valves, as well as related bypass and drain valve considerations where appropriate, turbine throttle and governor valves, steam dump/turbine bypass valves and associated isolation valves (if any), atmospheric dump and associated isolation valves, and secondary steam relief valves (SSRVs).

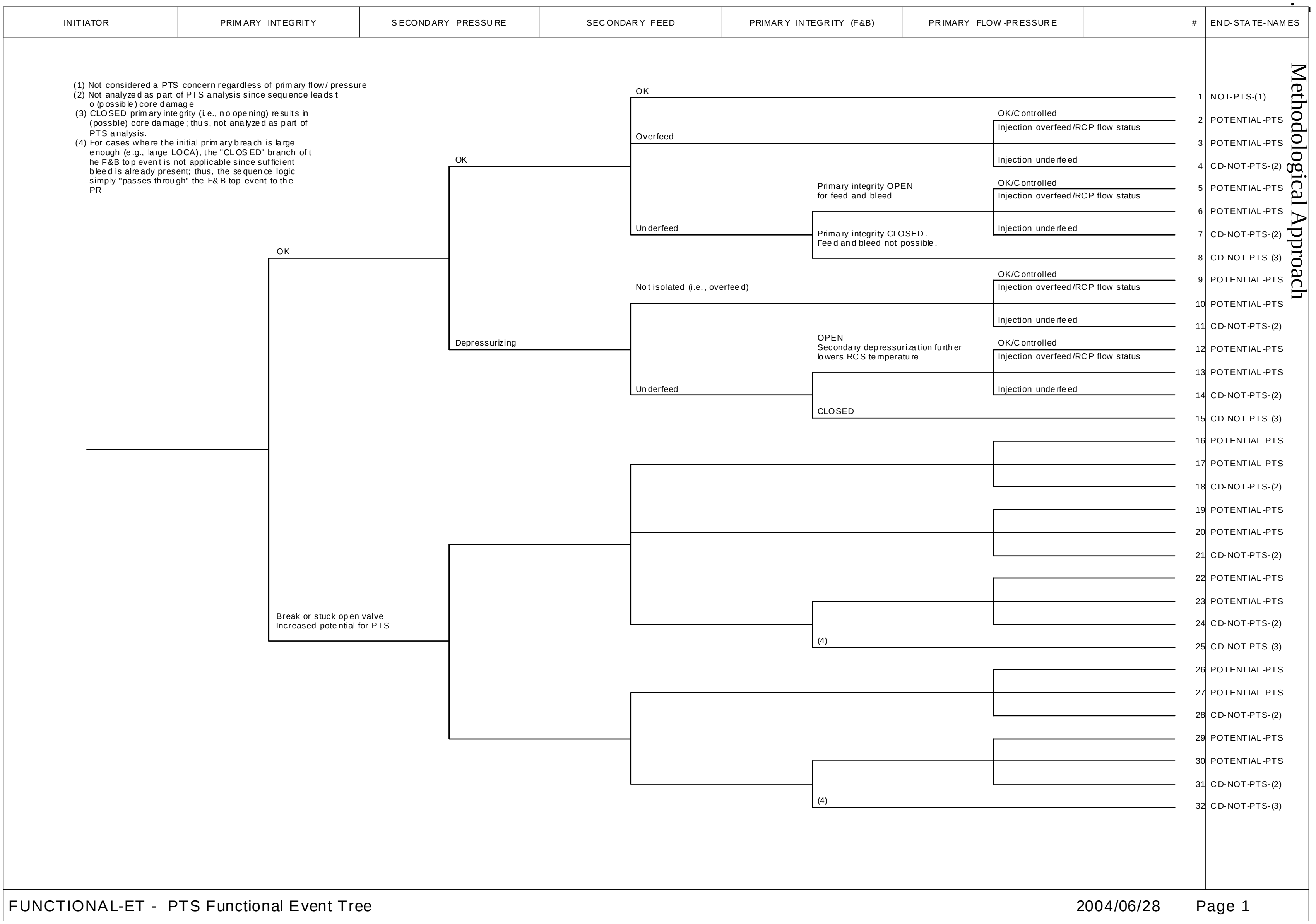

Figure 3. Functional event tree as the basis for PTS PRA analyses.

- Secondary feed: Status of main feedwater (MFW), condensate, and auxiliary/emergency feedwater (AFW/EFW) systems.

- Primary pressure/flow: Status of high head safety injection, charging pumps and letdown considerations, accumulators/safety injection tanks, low head safety injection, reactor coolant pumps (RCPs).

The status of other equipment that is relevant because of interactions with the equipment in this list is also modeled as appropriate. Such equipment includes the actuation and protection/isolation circuitry associated with the equipment in the preceding list, and support systems including cooling water, instrument air, and electric power and instrumentation. Heating and ventilation equipment was not considered in the analyses due to the slow effects of such a loss, and since the loss can often be easily identified and recovered.

3.2.4 Human Action Considerations

Plant records of overcooling events that have actually occurred demonstrate that operator actions and inactions can significantly influence the degree of overcooling and the RCS pressure for many types of overcooling events. Consequently, operator action directly influences, in both beneficial and detrimental ways, the potential for many types of event sequences to become serious PTS challenges. For example, early operator action to isolate the feed to a faulted (depressurizing or already depressurized) steam generator (SG), directly affects the amount of overcooling that occurs and/or how long such cooling is sustained. Consequently, any "realistic" PTS analysis needs to consider operator actions and inactions that influence overcooling sequences. Therefore, consistent with the guiding principles of this project to adopt best-estimate models and treat uncertainties explicitly whenever practicable, a rigorous treatment of human actions is included in the PRA models. The process to identify, model, and probabilistically quantify human factors derives largely from NUREG-1624, Revision 1 [NUREG 1624R1], which uses an expert elicitation approach. In this study the experts included both NRC contractors and licensees. These individuals considered both errors of omission and acts of commission. This process identified several general classes of human failures (see Table 2), which have been incorporated into the PRA models. Table 2 also indicates which of the four primary functions (identified in Section 3.2.3 and Figure 3) these failures most affect.

3.3 Step 3: Construct the PRA Models

The well-known and well-established event tree-fault tree PRA methodology was adopted as the basis for all plant specific analyses. However, the modeling approach varied somewhat from plant to plant because of the order in which the plants were analyzed (lessons learned in the Oconee analysis impacted the Beaver Valley and Palisades modeling approach, for example). Additionally, the availability of information from TH and PFM at the time PRA modeling began influenced how the PRA model evolved. A summary of the modeling approaches for Oconee, Beaver Valley, and Palisades is presented in the following two subsections.

3.3.1 PRA Modeling Differences Attributable to the Organization Constructing the Model

Both the Oconee and Beaver Valley PTS analyses use the same large event tree - small fault tree modeling format adopted by the PRAs that formed the technical basis for the current PTS rule. This approach makes best use of the earlier work in constructing updated PRA models. Since the desired

Table 2. General classes of human failures considered in the PTS analyses.

Primary Integrity Control	Secondary Pressure Control	Secondary Feed Control	Primary Pressure/Flow Control
I. Operator fails to isolate an isolable LOCA in a timely manner (e.g., close a block valve to a stuck- open PORV) II. Operator induces a LOCA (e.g., opens a PORV) that induces/enhances a cooldown	I. Operator fails to isolate a depressurization condition in a timely manner II. Operator isolates when not needed (may create a new depressurization challenge, lose heat sink...) III. Operator isolates wrong path/SG (depressurization continues) IV. Operator creates an excess steam demand such as opening turbine bypass/atmospheric dump valves	I. Operator fails to stop/throttle or properly align feed in a timely manner (overcooling enhanced or continues) II. Operator feeds wrong (affected) SG (overcooling continues) III. Operator stops/throttles feed when inappropriate (causes underfeed, may have to go to feed and bleed with its subsequent increase in potential for overcooling)	I. Operator does not properly control cooling and throttles/terminates injection to control RCS pressure II. Operator trips RCPs when not appropriate and/or fails to restore them when desirable III. Operator does not provide sufficient injection or fails to trip RCPs appropriately (failure to provide sufficient injection is modeled as leading to core damage; thus, such sequences are not PTS-relevant)

outputs do not require the explicit component faults for some of the systems included in the model, very simple system fault trees were used with corresponding system-level failure data to represent the failure or unavailability of these systems.

In contrast, a plant-specific PRA model developed by the licensee was used to provide the starting point for the PRA model of the Palisades plant used in this project. The licensee's PRA includes more detailed component-level fault trees for all the systems included in the PTS-PRA model. However, in all three analyses, the level of resolution in the results is sufficient for the purposes of assessing the PTS risk.

3.3.2 PRA Modeling Differences Attributable to the Order of Plant Analysis

The PRA model of Oconee was constructed first (at a time when feedback information from the TH analysis and from the PFM analysis was not yet available). Consequently, it was not possible to screen out of the model overcooling sequences having a benign TH response or very low estimated conditional probabilities of through wall cracking (from the PFM analysis). Hence, the Oconee PRA model contains virtually all the possible overcooling sequences with virtually no *a priori* screening out of "low significance" sequences. Subsequent feedback from both TH and PFM verified that many of the sequences included in the Oconee model could justifiably been omitted from the PRA model.

Work on the Beaver Valley PRA model was initiated after the Oconee model had been constructed, at a time when the Oconee analysis results, while still evolving, were generally well understood. Also, as the Beaver Valley PRA model was being constructed, some advanced TH and PFM results were already available for Beaver Valley sequences–identified from "lessons learned" from the Oconee analysis. Consideration of this Beaver Valley TH/PFM information permitted *a priori* screening of the following general categories of sequences from the Beaver Valley PRA model:

- Sequences involving certain combinations of stuck-open pressurizer PORVs or SRVs were not modeled

- Sequences involving certain combinations of secondary valve and simultaneous pressurizer PORV/SRV stuck-open events were not modeled

- Sequences involving only secondary valve (single or multiple) stuck-open events were not modeled

- Sequences involving overfeed of various SG combinations were not modeled

- Sources of secondary depressurization downstream of the MSIVs were not explicitly modeled

- SGTR sequences were not modeled including even those involving lack of proper feed control and even with RCPs shutdown (possibly inducing RCS loop stagnation)

- Other sequences were screened from modeling on a case-by-case basis if the sequence frequency could be conservatively estimated as less than $\sim 10^{-8}$/yr. This screening criterion was used because, when coupled with the maximum CPF calculated for any type of sequence (in the 10^{-3} range) a TWCF of $<10^{-11}$/yr would be generated. Such frequencies would clearly not be important to the overall PTS results since some other sequences were known to involve TWCFs in the 10^{-8}/yr range.

Because the Palisades model was built starting with an already established licensee component-level PRA model with overcooling sequences, it is the most detailed model of the three. This pre-existing Palisades model was augumented by the licensee, on the basis of NRC contractor review and input, to include possible scenarios and other factors not already in the pre-existing model. Consequently, the "lessons learned" from the Oconee PRA influenced the Palisades PRA model as well. In general, the Palisades PRA model addresses the same types of initiators and sequences as do the Oconee and Beaver Valley models. However, with few exceptions, the initiating event frequencies, equipment failure probability data, and human failure estimates are specific to Palisades.

3.4 Step 4: Quantify and Bin the PRA Modeled Sequences

For each plant, two conditions were modeled: full operating power and hot zero power (HZP). As identified in Section 3.3.2, little information was available to screen out potential PTS sequences for Oconee. Thus, because of a SAPHIRE code [SAPHIRE] limitation (i.e., the inability to store more than 100,000 sequences in a data base)[3], it became necessary to produce separate SAPHIRE models for power and for HZP. Once the models (i.e., the event trees and fault trees) were constructed, the SAPHIRE code was used to generate the sequence logic for each event tree, and to solve the resulting sequences (90,629 sequences for each model) with no truncation due to frequency.

Given the number of potential PTS sequences for Oconee (181,258), it was necessary to group (i.e., bin) sequences with like characteristics into representative TH cases for analysis using RELAP [NUREG/CR-6858][4].

[3]This limitation has been removed from the current version of the software.

[4]This same binning process was used for Beaver Valley and Palisades, though the number of sequences to bin was smaller.

Initial bins were constructed by developing event tree partitioning rules in SAPHIRE and then applying these rules to produce the TH bins. Development of the partitioning rules required the analysts to examine the TH information available from preliminary analyses to identify the characteristics that would be important to the binning process.

Using this information, the analysts then made judgments as to whether existing TH characteristics could be used to represent new groups of sequences. If the analysts judged that existing characteristics were appropriate, either because they matched the examined sequences exactly or because the TH conditions from the new sequences were expected to be similar to but not be worse than the conditions from the existing analysis, then the uniquely-defining characteristics associated with the existing TH analyses were written in rule form for application in SAPHIRE. For those cases where the analysts were sufficiently unsure as to the appropriateness of using existing characteristics, new TH characteristics were identified. These new sets of characteristics were discussed with the TH analysts. If after discussion with the TH analysts, it was concluded that the expected TH conditions could be sufficiently different from prior TH analyses and that the frequency of occurrence of the conditions was such that it could not be “added” to some existing TH bin without being unnecessarily conservative, then a new TH calculation was identified. The TH characteristics associated with this new calculation were then written in rule form for subsequent application in SAPHIRE.

This iterative process continued until all accident sequence cut sets were associated with a specific TH bin. Thus, the final application of the developed rules involved the examination of each sequence cut set to determine which rule the cut set met, the subsequent “tagging” of the cut set, and the gathering of like-tagged cut sets into initial TH bins. Once all cut sets were gathered into the initial TH bins, the bins were re-quantified using a truncation limit of 1E-10/yr.

For Beaver Valley, essentially the same process was followed. The major difference between the Oconee and Beaver Valley analyses was in the number of sequences developed and solved (a total of 8,298 sequences for Beaver Valley for power and HZP). As discussed in the previous subsection, knowledge about what was and was not important in the Oconee analysis was used with preliminary sequence frequency estimates and CPFs results from early Beaver Valley TH and PFM calculations to minimize the number of sequences actually modeled in the corresponding SAPHIRE data bases. Given the significantly fewer number of sequences, no truncation was performed on the initial TH bins.

For Palisades, the process was somewhat different in that the SAPHIRE model included both power and HZP sequences in the same data base (only 3425 sequences total) and the sequences were solved using a 1E-9/yr truncation value. Another difference between the Palisades and Oconee or Beaver Valley analyses was how the TH bins were created. In the Palisades analysis, each sequence end state was defined to a specific TH bin and all resulting cut sets were placed in the defined bin. (Note: use of this binning process rather than the one used in the Oconee or Beaver Valley analyses did not have any significant impact on the results which are similar across the three plants. It is simply that the binning process was somewhat more crude to expedite the analysis process.)

3.5 Step 5: Revise PRA Models and Quantification

With preliminary results available, reviews by both licensee and internal project staff were conducted. This allowed for formal feedback from the licensee with regard to the PTS-PRA models, inputs, assumptions, and results, and provided an opportunity for analysts’ self-review of the PRA to date. The purposes of the reviews were to determine:

- whether inaccuracies existed in the models, and whether additional potential PTS sequences needed to be modeled,

- whether additional TH bins should be created to reduce unnecessary conservatism based on new or updated information obtained from preliminary CPF calculations or needs identified by the uncertainty analysis,

- which human actions were associated with the important TH bins,

- which of these human actions should be reexamined to produce even more realistic (i.e., less conservative) human error probabilities (HEPs), and

- what combination of the above could be accomplished within the constraints of the project.

For Oconee, the reviews identified the need:

- to add one more type of potential PTS sequence,

- for additional TH bins to address uncertainty issues and to reduce conservatism (Note: conservatism is not reduced by having too many sequences represented by a bin that is described by plant conditions that are too conservative for the actual conditions of the sequences), and

- to reexamine some human actions to produce updated HEPs to account for more specific conditions.

The Beaver Valley reviews identified the need:

- for additional TH bins to address uncertainty issues and to reduce conservatism, and

- to reexamine a few human actions to produce updated HEPs to account for more specific conditions.

Because the Palisades analysis was being performed by the utility, the results of the review described here dealt only with issues identified by the NRC review of the licensee's PTS model. The review identified the need:

- to add additional break sizes to the LOCA class of initiating events,
- to modify probabilities for a few selected basic events, and
- for additional TH bins to address uncertainty issues.

It should be mentioned that while formal reviews were performed, such as during the second plant visit at both Oconee and Beaver Valley, informal periodic review was conducted via the written and vocal communications among the licensees and project staff on a frequent basis. Appropriately, the models were revised and re-quantification was performed on the basis of these licensee inputs and as a result of self-evaluations by the project staff.

3.6 Step 6: Perform Uncertainty Analyses

The primary objective of the PRA portion of the PTS analyses was to produce estimates of the frequencies for each set of plant scenarios that comprise the TH bins developed in Step 4. As discussed previously, these scenarios involve initiating events, mitigating equipment successes and failures, and operator actions that result in various degrees of overcooling of the internal reactor vessel downcomer wall. The major areas of uncertainty associated with the PRA can be grouped into two broad categories:

- modeling of the representative plant scenarios, and
- estimation of the frequency of each modeled scenario.

These areas of uncertainty and the techniques used to deal with the uncertainties are discussed in the following two subsections.

3.6.1 Modeling of Representative Scenarios to Characterize Aleatory Uncertainty

Each scenario in the PRA is represented by a collection of events described by the logic of the event tree and relevant fault trees for each initiating event identified in the analysis. The model initially assumed binary logic (e.g., valve fully re-closes or sticks wide open; no in-between states) for the events. The only explicit modeling of event timing involved the timing of operator actions (i.e., failure to take an action is modeled as failure to take that action in multiple discrete times–for example, by 10 min, by 20 min–each with a probability). Most uncertainties with regard to the model structure (e.g., completeness, in-between states) are not quantified. However, where judged potentially important, a few aleatory uncertainties were addressed by purposely changing the model and assigning a probability to the applicability of the model change. Each of these changes becomes a different scenario (TH bin) with an associated frequency (e.g., area associated with a stuck open SRV reduced 30%, timing of reclosure of a stuck open SRV, actual break size of small and medium LOCAs). Since it is unknown which scenario will occur following an initiating event, the complete set of scenarios, as represented by the event trees, characterize a large part of the aleatory uncertainty associated with the occurrence of a PTS challenge. The most important of these uncertainties that were handled explicitly in the analyses are addressed further in the next step, Step 7.

In addition, there is the overall general uncertainty as to the completeness issue (i.e., have all scenarios that potentially lead to PTS conditions been identified and modeled). This uncertainty issue was addressed non-quantitatively through both internal (i.e., NRC and its contractors) and external (i.e., licensee) review of the PRA model. As a result of this peer review process, the models are expected to produce a sufficiently complete set of potential PTS sequences and thus, any incompleteness in the model is expected to have a small effect on the results.

3.6.2 Quantification of Scenario Frequencies to Characterize Epistemic Uncertainty

Each scenario from the set of modeled scenarios is the interaction of what are treated as random events:

- initiating event,

- series of mitigating equipment successes/failures (e.g., MFW trips, AFW starts, atmospheric dump valves (ADVs) are challenged and one sticks open…), and

- operator actions (e.g., fails to close ADV isolation valve by 20 minutes after the ADV sticks open).

Thus, the occurrence of each scenario is random, and the frequency of each scenario is obtained by:

$$f_{\text{scenario}} = f_{\text{initiating event}} \cdot Pr_{\text{equipment response}} \cdot Pr_{\text{operator action(s)}} \qquad \text{(Eq. 1)}$$

where f denotes a frequency and Pr denotes a probability.

Each of the variables used to obtain the scenario frequency has an epistemic uncertainty described by a distribution. The source of this information came primarily from the input data used in the analysis; i.e., the addendum to NUREG/CR-5750 [INEEL 00b] for Oconee and Beaver Valley, and the plant-specific data used in the Palisades analysis. For a few specific model inputs, other data sources were also used to derive these uncertainty estimates. For the HEPs, both best estimate values and uncertainty ranges and distributions were derived through the expert elicitation processes carried out in the human reliability analyses. Latin Hypercube sampling techniques were used to propagate these epistemic uncertainties to generate a probability distribution for each scenario frequency, which subsequently yielded the uncertainty in the TH bin frequency. Thus, the frequencies provided by the PRA analysts to the PFM analysts were described by histograms representing the resulting frequency distributions. In this way, these PRA uncertainty distributions were propagated through and combined with the PFM uncertainties to ultimately derive uncertainty distributions in the estimated TWCFs.

3.7 Step 7: Incorporate Uncertainty and Finalize Results

This section discusses important uncertainties (largely aleatory in nature) specifically addressed in the PRA and describes how each was handled. As described in the previous subsection, epistemic uncertainty in the frequency for each of the final TH bins was estimated using Latin Hypercube sampling techniques and will not be described in this subsection.

The uncertainties below were dealt with quantitatively; however, the degree of resolution associated with each specific uncertainty was limited. These uncertainties include:

- size of the LOCA within a LOCA category plus other factors (e.g., initial injection water temperature),
- size of the opening associated with a single or multiple stuck open SRV(s),
- time at which a stuck open SRV recloses, and
- time at which operators take or fail to take action.

These uncertainties were highlighted for specific treatment in the analysis based on (a) the scenarios found to be most important to the PTS results, and (b) a series of uncertainty analyses performed by the University of Maryland (UMD) project team members on many of the inputs and parameters potentially affecting the PTS results to see which uncertainties would most affect those results. The specific UMD analyses are discussed in [Chang]. The results of that work concluded that the above uncertainties are sufficiently important that they needed to be treated explicitly in the PRA model. These uncertainties and how they were addressed are discussed in the following paragraphs.

The actual break size of a LOCA for a specific LOCA class (i.e., small, medium, or large) can be any point on the spectrum of sizes defined by the two end points for that class. In addition, other factors (e.g., initial injection water temperature, break location, and injection flow rate) can contribute to the overall PTS model uncertainty since these factors along with the specific break size affect the rate of cooling and subsequent plant response. Numerical probability results from the UMD uncertainty analysis were used to model and estimate the importance of the various modeling uncertainties examined in the UMD analysis, including the different break sizes within a given class (which was assumed to be uniformly distributed). These numerical analyses provided a spectrum of different plant TH responses arising from uncertainties in these key parameters including break size. This spectrum of results was then represented by a number of discrete cases to cover the total spectrum of results (typically, five cases for small LOCAs, three for medium LOCAs, and one for large LOCAs). Each case was assigned a probability by the UMD analysts based on how much of the total spectrum the discrete case represented. Each discrete case was assigned a new TH case number with corresponding TH curves, and the frequency of each new case was adjusted using the UMD assigned probability for that case. This was accomplished by:

- gathering all cut sets from all sequences generated for a specific LOCA class into one bin,
- reproducing the gathered cut sets a specified number of times corresponding to the number of discrete cases defined to represent the spectrum of results, and
- modifying each set of reproduced cut sets to include the probability assigned that discrete case.

Thus, the new modified cut sets account for the uncertainty associated with various parameters examined in the UMD analysis, including possible variation of break sizes within a given LOCA class.

Just as with the LOCAs, the size of the opening associated with a stuck open SRV can vary from sizes that are not PTS-significant to the valve fully stuck open. To deal with this issue and other relevant issues examined in the UMD analysis, the cut sets (and their associated frequencies) from stuck-open SRV sequences were modified to include a fraction that represented the uncertainty from the UMD work. In this case, it was assumed that the SRV opening size is uniformly distributed (any specific opening is equally likely) and the resulting fraction was included in the sequence frequency estimates to account for that fraction of possible SRV size openings that would be sufficient, from a cooling perspective, to be potentially important.

The time at which a stuck-open SRV recloses is unknown and can occur at any point after the valve sticks open. To approximate this, the frequencies associated with stuck-open SRV sequences with subsequent closure of the SRV were divided equally between two specific SRV reclosure times (i.e., 3000 s and 6000 s). These two time points were chosen after reviewing stuck-open SRV TH conditions. The 6000 s point was chosen to coincide with the time when the change in downcomer wall temperature had “flattened out.” The 3000 s point was chosen to coincide with the time when sufficient cooling had occurred to the downcomer wall such that PTS could become an issue. Use of these two times provides a mechanism for determining some measure of the uncertainty associated with reclosure of stuck open SRVs[5, 6]. Each case

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[5]An enhancement that should be considered for any subsequent analyses entails performing multiple TH and PFM calculations for differing valve closure times (e.g., 1000 to 8000 seconds in increments of 1000 seconds) to determine when the CPF peaks. The time at which the CPF peaks can then be used as one of the modeled reclosure times (i.e. the latest reclosure time). Care should be taken to ensure that the selected reclosure time point does not occur after the operators are expected to have transitioned from responding to the initiating event to placing the plant in cold shutdown (e.g., 7200 seconds).

[6]Subsequent sensitivity analyses demonstrated that the 6000 s time is nearly the worst time from a PTS challenge point of view. The worst conditional probability of vessel failure typically occur if the SRV is assumed to close at 7000 s or a little beyond, with vessel failure probabilities within a factor of ~2 of those calculated for 6000 s.

was assigned a 50% chance of occurring.

Just as the time at which a stuck-open SRV recloses is unknown, so too are the times at which operators perform actions. To address this issue, the times at which selected operator actions (i.e., those believed to be relatively important to PTS) were performed were varied. Typically, two or three different times were chosen to represent the uncertainty in when the action would be performed. Once the times were defined, typically (1) as early as could be expected, (2) as late as possible that would still affect the outcome, and (3) for some actions, some intermediate time, the probability of failing to perform the action by the specified time was developed. Use of these operator action times provides a means of estimating the uncertainty associated with when the operators actually perform their actions.

For the Oconee analysis, all issues identified above were incorporated into the analysis. For the Beaver Valley and Palisades analyses, results from the UMD analysis indicated that little uncertainty came from the sequences involving stuck-open SRVs that remained stuck open; thus, no modifications were made to those types of sequences in the Beaver Valley and Palisades analyses. However, all other modifications were made for the analyses of Beaver Valley and Palisades.

4. SUMMARY

This report summarizes the overall process used to develop and quantify the Oconee, Beaver Valley, and Palisades PTS PRA models used to support the PTS re-analysis project. Similarities and differences among the development of the models are discussed.

For more details on the individual analyses see [Kolaczkowski 04b] for Oconee, [Whitehead 04a] for Beaver Valley, and [Whitehead 04b] for Palisades.

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10. SUPPLEMENTARY NOTES

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11. ABSTRACT *(200 words or less)*

This report supplements NUREG-1806, “Technical Basis for Revision of the Pressurized Thermal Shock (PTS) Screening Limit in the PTS Rule (10CFR50.61): Summary Report,” with additional information regarding the Probabilistic Risk Assessment (PRA) and Human Reliability Analysis (HRA) portions of the PTS analyses presented in that report, including the use of realistic input values and models and an explicit treatment of uncertainties. Best estimate equipment failure values are used throughout based on generic nuclear industry data, or, in cases where it's available, on plant-specific data. Parameters related to human performance are based on plant specific review of procedures and training, observation of plant personnel responding to PTS-related sequences on their simulator, and performance data from actual plant operations.

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