ANP-10278NP
Revision 0

U.S. EPR Realistic Large Break Loss of Coolant Accident

Topical Report

March 2007

AREVA NP Inc.

Non-Proprietary

The design, engineering and other information contained in this document have been prepared by or on behalf of AREVA NP Inc., a jointly owned subsidiary of AREVA and Siemens, in connection with its request to the U.S. Nuclear Regulatory Commission for a pre-application review of the U.S. EPR nuclear power plant design. No use of or right to copy any of this information, other than by the NRC and its contractors in support of AREVA NP's pre-application review, is authorized.

The information provided in this document is a subset of a much larger set of know-how, technology and intellectual property pertaining to an evolutionary pressurized water reactor designed by AREVA NP and referred to as the U.S. EPR. Without access and a grant of rights to that larger set of know-how, technology and intellectual property rights, this document is not practically or rightfully usable by others, except by the NRC as set forth in the previous paragraph.

For information address: AREVA NP Inc.

An AREVA and Siemens Company

3315 Old Forest Road

Lynchburg, VA 24506

U.S. Nuclear Regulatory Commission

Disclaimer

Important Notice Concerning the Contents and Application of This Report

Please Read Carefully

This report was developed based on research and development funded and conducted by AREVA NP Inc., and is being submitted by AREVA NP to the U.S. Nuclear Regulatory Commission (NRC) to facilitate future licensing processes that may be pursued by licensees or applicants that are customers of AREVA NP. The information contained in this report may be used by the NRC and, under the terms of applicable agreements with AREVA NP, those customers seeking licenses or license amendments to assist in demonstrating compliance with NRC regulations. The information provided in this report is true and correct to the best of AREVA NP's knowledge, information, and belief.

AREVA NP's warranties and representations concerning the content of this report are set forth in agreements between AREVA NP and individual customers. Except as otherwise expressly provided in such agreements with its customers, neither AREVA NP nor any person acting on behalf of AREVA NP:

- Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, nor the use of any information, apparatus, method, or process disclosed in this report.
- Assumes any liability with respect to the use of or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

Nature of Changes

Item	Section(s) or Page(s)	Description and Justification

Contents

Page

List of Tables

Page

List of Figures

Page

Nomenclature

Acronym	Description
CCFL	Counter Current Flow Limit
CCTF	Cylindrical Core Test Facility
CCW(S)	Component Cooling Water (System)
CHF	Critical Heat Flux
CSAU	Code Scaling, Applicability, and Uncertainty
CVCS	Chemical and Volume Control System
DC	Downcomer
DCD	Design Control Document
DEGB	Double-Ended Guillotine Break
DNB(R)	Departure from Nucleate Boiling (Ratio)
EBS	Extra Borating System
ECCS	Emergency Core Cooling System
EDG	Emergency Diesel Generator
EM	Evaluation Model
FLECHT	Full Length Emergency Cooling Heat Transfer
HFP	Hot Full Power
HZP	Hot Zero Power
IRWST	In-Containment Refueling Water Storage Tank
LBLOCA	Large Break LOCA
LHGR	Linear Heat Generation Rate
LHSI	Low Head Safety Injection
LOCA	Loss-of-Coolant Accident
LOFT	Loss of Fluid Test
LOOP	Loss of Offsite Power
MFW(S)	Main Feedwater System
MHSI	Medium Head Safety Injection
MSLB	Main Steam Line Break
MTC	Moderator Temperature Coefficient
NSSS	Nuclear Steam Supply System
PCT	Peak Cladding Temperature
PDTF	Product Development Test Facility
PIRT	Phenomena Identification and Ranking Table
PLHGR	Planar Linear Heat Generation Rate
PWR	Pressurized Water Reactor
PZR	Pressurizer
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RHR(S)	Residual Heat Removal (System)
RLBLOCA	Realistic Large Break LOCA
RPV	Reactor Pressure Vessel

Acronym	Description
SBO	Station Blackout
SEASET	System Effects and Separate Effects Tests
SCTF	Slab Core Test Facility
SG	Steam Generator
SIS	Safety Injection System
SMART	Small Array Reflood Test
SS	Steady-State
THTF	Thermal-Hydraulic Test Facility
UH	Upper Head
UPTF	Upper Plenum Test Facility
W/EPRI	Westinghouse/Electric Power Research Institute
ΔP	Pressure Difference

1.0 INTRODUCTION

The purpose of this report is to describe and demonstrate the applicability of AREVA NP's NRC-approved Realistic Large Break LOCA Evaluation Model to the U.S. EPR. This methodology is described in detail in the topical report EMF-2103(P)(A), "Realistic Large Break LOCA Methodology for Pressurized Water Reactors" (Reference 1). In subsequent sections of this report, this Realistic LBLOCA (RLBLOCA) methodology will be demonstrated to be applicable to the U.S. EPR without modification.

The U.S. EPR is an evolutionary Pressurized Water Reactor (PWR) design and retains the principal features of existing four-loop plants and fuel designs. Section 2 provides a brief overview of the U.S. EPR, focusing on features important for mitigation of LBLOCA events.

Sections 3 though 5 of this report contain an overview of the LBLOCA codes and methods, a discussion of important phenomena, and the bases for applying the code/methods to the U.S. EPR. The applicability of the methodology is demonstrated in part by comparing physical characteristics of existing plants and fuel designs having approved methods to the corresponding physical characteristics of the U.S. EPR. In addition, applicability is demonstrated by showing that phenomena occurring in existing plants are the same as those for the U.S. EPR and that the phenomena are adequately modeled by the codes.

Report conclusions appear in Section 6, and Appendix A contains LBLOCA sample calculations.

2.0 U.S. EPR DESIGN OVERVIEW

The U.S. EPR is an evolutionary PWR with a rated core thermal power of 4,590 MWt. The primary system design, loop configuration, and main components are similar to those of currently operating PWRs, thus forming a proven foundation for the design.

The U.S. EPR has a four-loop Reactor Coolant System (RCS) composed of a Reactor Pressure Vessel (RPV) that contains 241 fuel assemblies, a pressurizer (PZR) including control systems to maintain system pressure, one Reactor Coolant Pump (RCP) per loop, one Steam Generator (SG) per loop, associated piping, and related control and protection systems.

The RCS is contained within a concrete containment building. The containment building is enclosed by a shield building with an annular space between the two buildings. The pre-stressed concrete shell of the containment building has a steel liner and the shield building wall is reinforced concrete. The Containment and Shield Buildings comprise the Reactor Building. The Reactor Building is surrounded by four Safeguard Buildings and a Fuel Building (see Figure 2-1). The internal structures and components within the Reactor Building, Fuel Building, and two Safeguard Buildings (including the plant Control Room) are protected against aircraft hazard and external explosions. The other two Safeguard Buildings are not protected against aircraft hazard or external explosions; however, they are separated by the Reactor Building, which restricts damage from these external events to a single safety division.

Four 100% capacity safety systems are separated into four divisions (one per Safeguard Building). The four divisions of safety systems are consistent with an N+2 safety concept. With four divisions, one division can be out-of-service for maintenance and one division can fail to operate, while the remaining two divisions are available to perform the necessary safety functions even if one is ineffective due to the initiating event.

In the event of a loss of off-site power (LOOP), each safeguard division is powered by a separate Emergency Diesel Generator (EDG). In addition to the four safety-related diesels that power various safeguards, two independent diesel generators are available to power essential equipment during a postulated Station Blackout (SBO) event—loss of offsite AC power with coincident failure of all four EDGs.

Water storage for safety injection is provided by the In-containment Refueling Water Storage Tank (IRWST). Also inside containment, below the RPV, is a dedicated spreading area for molten core material following a postulated worst-case severe accident.

The fuel pool is located outside the Reactor Building in a dedicated building to simplify access for fuel handling during plant operation and handling of fuel casks. As stated previously, the Fuel Building is protected against aircraft hazard and external explosions. Fuel pool cooling is assured by two redundant, safety-related cooling trains.

Although the U.S. EPR embodies a number of improvements on existing PWR designs, these improvements are evolutionary and U.S. EPR design conditions are similar to operating PWRs. Reference 2 (Tables 2-1 through 2-4) contains comparisons of U.S. EPR design parameters and those of contemporary plants.

2.1 *U.S. EPR Plant Design and Features*

Reference 2 describes the U.S. EPR core design, the RCS and its principal components, overpressure (primary and secondary) protection, and the principal fluid systems. That discussion will not be repeated here. However, there have been changes to the Safety Injection System/Residual Heat Removal System (SIS/RHRS) since Reference 2 was published. Since these changes affect the LBLOCA response, a description of the SIS/RHRS and the modifications follow.

2.2 *Safety Injection System/Residual Heat Removal System (SIS/RHRS)*

The SIS/RHRS performs normal shutdown cooling, as well as emergency coolant injection and recirculation functions to maintain reactor core coolant inventory and provide adequate decay heat removal following a LOCA. The SIS/RHRS also can maintain RCS inventory following a Main Steam Line Break (MSLB).

2.2.1 *SIS/RHRS Description and Operation*

The SIS/RHRS consists of four trains, each providing injection capability using an accumulator pressurized with nitrogen gas, a Medium Head Safety Injection (MHSI) pump, and a Low Head Safety Injection (LHSI) pump. The LHSI pumps also perform the operational functions of the RHRS. (Figure 2-2 is a flow schematic of a single train of the SIS/RHRS.) Each of the four SIS trains is provided with a separate suction connection to the IRWST. Guard pipes are provided for sump suction piping between the sump connection and the suction isolation valve. The sumps are provided with a series of screens, providing protection of the SIS pumps against debris entrained with IRWST fluid.

Each pump is provided with a miniflow (minimum flow) line routed to the IRWST. The miniflow lines prevent pump dead-heading when the RCS pressure is greater than the pump discharge pressure. The LHSI/RHR pump miniflow line also provides cooling and mixing of the IRWST.

In the injection mode, the MHSI and LHSI/RHR pumps take suction from the IRWST and inject into the RCS through nozzles located in the side of the piping. These pumps are located in the Safeguard Buildings, close to the containment. The LHSI/RHR pumps and the MHSI pumps normally inject into the cold legs. In the long term following a LOCA, the LHSI discharge can be switched over to the hot legs to limit the boron concentration in the core, thus reducing the risk of crystallization in the upper part of the core.

An LHSI/RHR heat exchanger is located downstream of each LHSI/RHR pump. These heat exchangers are installed in the Safeguard Buildings and cooled by the CCWS. The accumulators are located inside the containment and inject into the RCS cold legs when the RCS pressure falls below the accumulator pressure, using the same injection nozzles as the LHSI/RHR and MHSI pumps.

During RHR operation, the LHSI/RHR pumps take suction from the RCS hot leg and discharge through the LHSI/RHR heat exchangers back to the RCS cold leg. During shutdown, the LHSI/RHR pump is used in the RHR mode, but the MHSI pump remains available for water makeup in the event of a LOCA.

All four SIS/RHRS trains are powered from separate emergency buses, each backed by an EDG. The LHSI/RHR pumps in Trains 1 and 4 are also backed-up by the SBO diesels. One SIS/RHRS train is located in each of the Safeguard Buildings, thereby providing separation and/or physical protection from external and internal hazards.

2.2.2 *SIS/RHRS Modifications*

A subsequent change to the design which potentially impacts LBLOCA response is the addition of cross-connects in the SIS/RHRS. Under normal operating conditions, all four trains of SIS/RHRS are separate and independent. However, during online maintenance of an LHSI train, valves are opened to connect the discharge lines of train 1 to train 2 and of train 3 to train 4. In the unlikely event of a LBLOCA coincident with maintenance of an LHSI train and with an assumed single failure of an additional LHSI train, the connections ensure a more even distribution of safety injection to the cold legs. Figure 2-3 shows the location of the cross-connects for the four SIS/RHRS trains. Figure 2-2 also notes the cross-connect attachment location in the flow schematic of a complete SIS/RHRS train. The cross-connect attachment points are made to the LHSI piping upstream of the LHSI/MHSI connection. Check valves prevent MHSI flow from entering the cross-connects. Therefore, only the LHSI (not MHSI) is split between cold legs. The cross-connects are active only when one LHSI train has been taken out of service for maintenance. Isolation valves are installed on the cross-connect piping and are open only during maintenance.

Figure 2-1 General U.S. EPR Layout

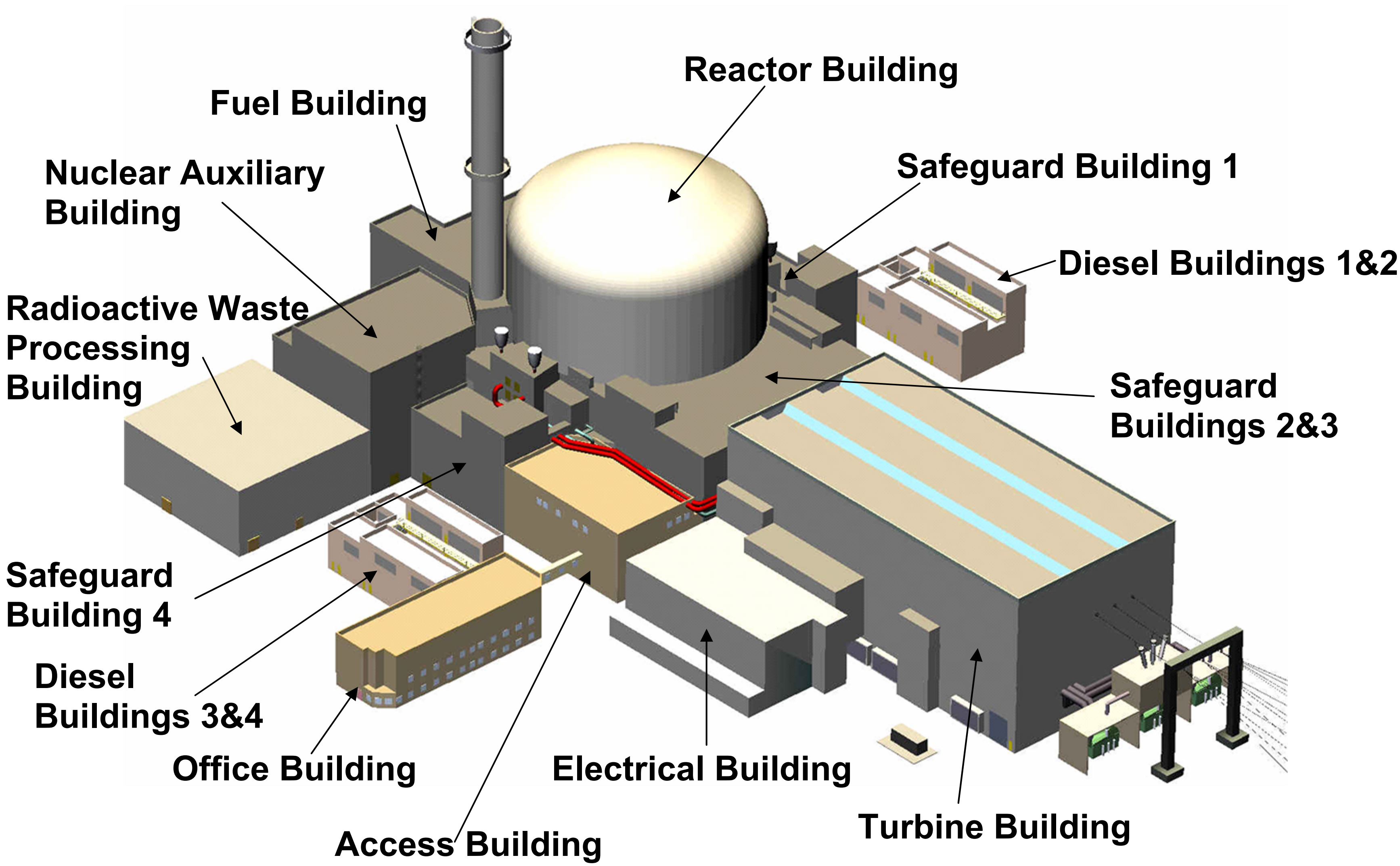


Figure 2-2 Safety Injection System/Residual Heat Removal System

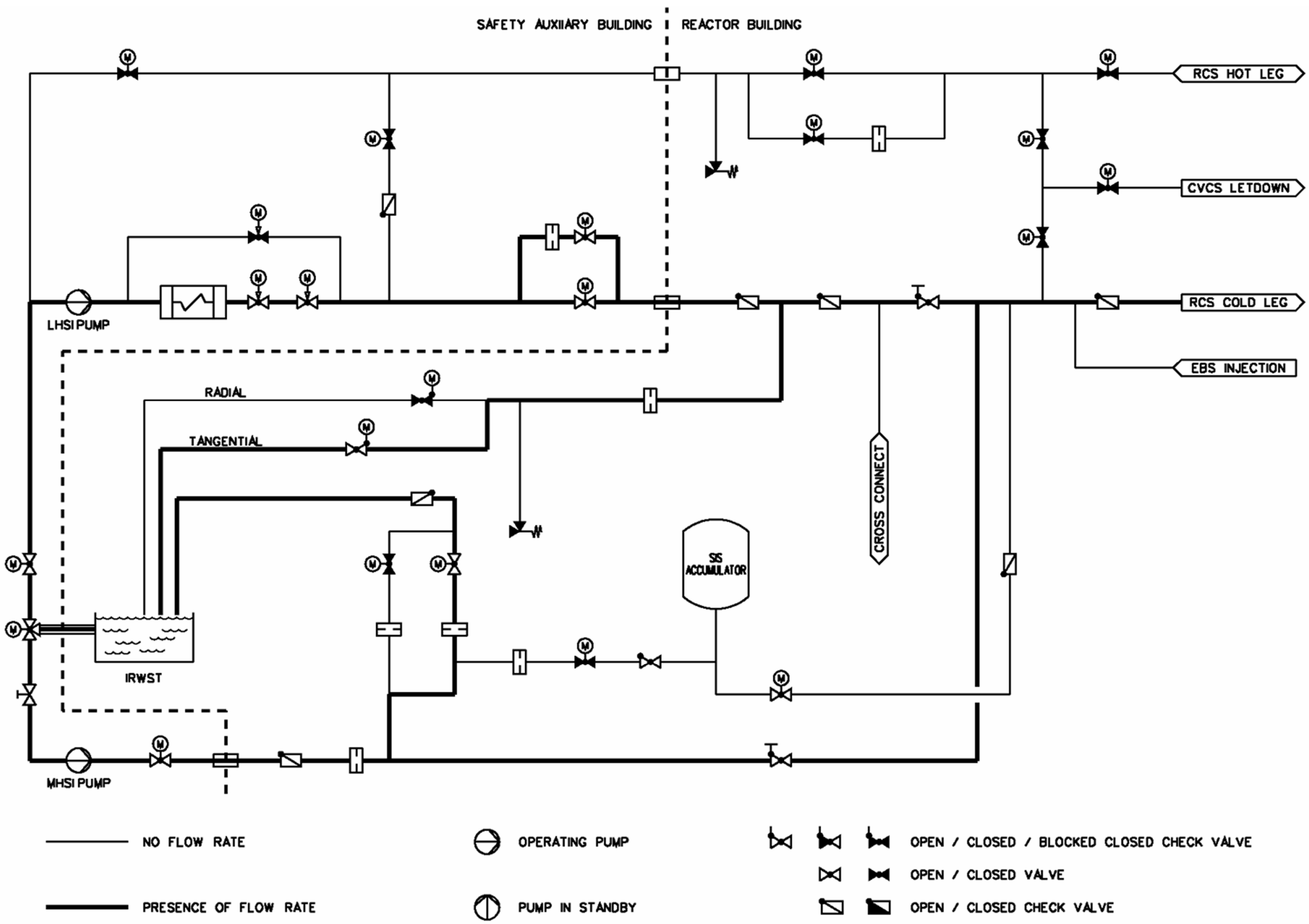
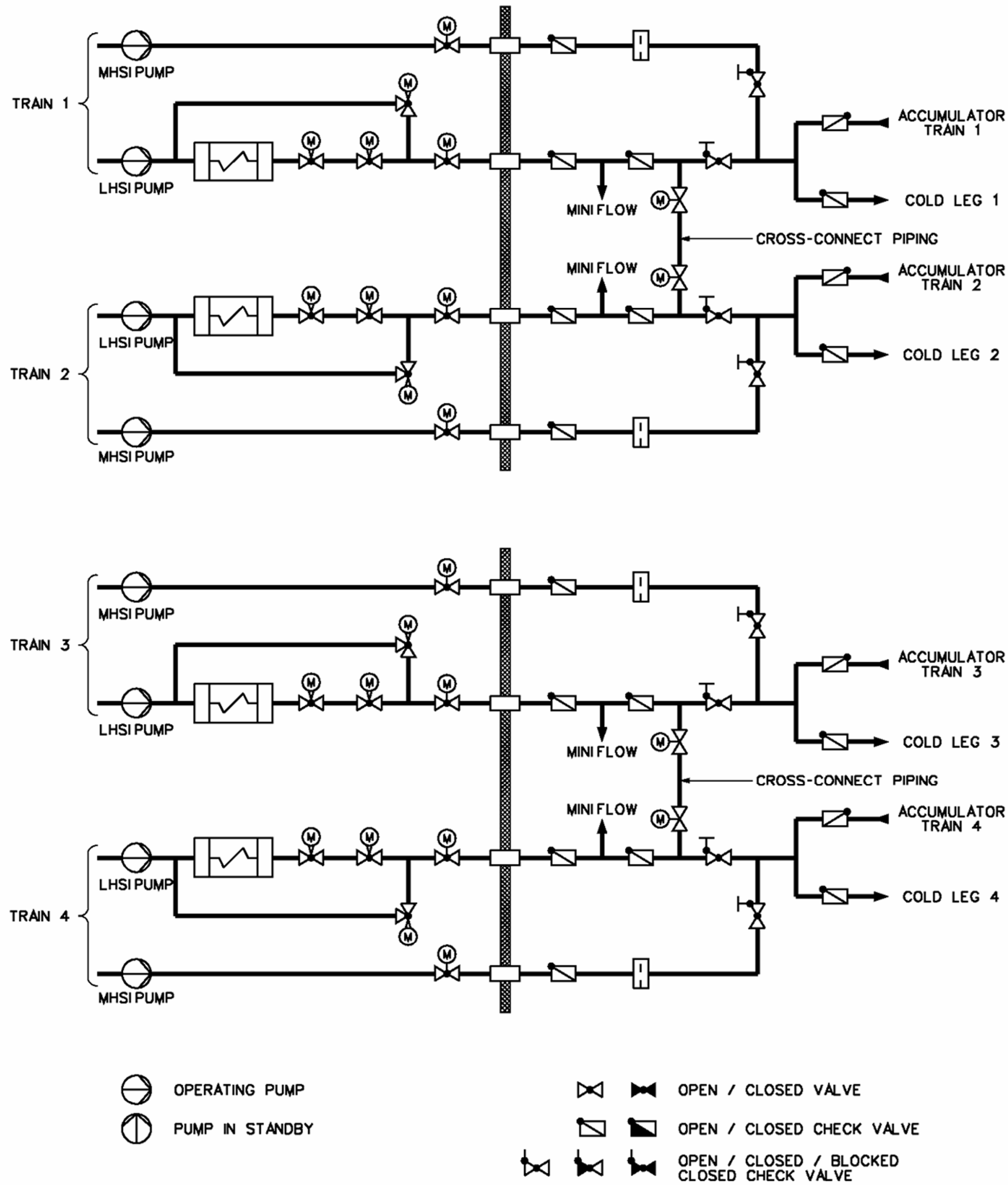


Figure 2-3 Cross-Connect Piping Location



3.0 LARGE BREAK LOCA CODES AND METHODS

As noted in the Introduction, the purpose of this report is to briefly describe and then to demonstrate the applicability of AREVA NP's NRC-approved, Realistic LBLOCA Evaluation Model (RLBLOCA EM, Reference 1) to the U.S. EPR. Currently, the methodology is approved for application to Westinghouse 3- and 4-loop plants and Combustion Engineering (CE) designed plants. As will be demonstrated, the RLBLOCA EM is applicable to the U.S. EPR without modification because of its similarity to current 4-loop plants in design, geometry, functionality and phenomenological response to a LBLOCA.

AREVA NP's RLBLOCA EM is a best-estimate methodology formulated using non-parametric statistics. The methodology follows the Code Scaling, Applicability, and Uncertainty (CSAU) evaluation methodology (Reference 3). The CSAU method outlines an approach for defining and qualifying a best-estimate thermal-hydraulic code and quantifies the uncertainties in a LOCA analysis. Some three dozen key phenomenological and plant parameters are sampled (see Table 3-1) in each transient calculation. Peak Cladding Temperature (PCT) is predicted at the 95 percent probability level with 95 percent confidence. The computer code is S-RELAP5, an AREVA NP-developed code that is based on INEL's RELAP5/MOD2 and /MOD3 code series. The EM complies with 10CFR50.46 requirements.

The RLBLOCA methodology consists of the following computer codes:

- RODEX3A for computation of the initial fuel stored energy, fission gas release, and fuel-cladding gap conductance.
- S-RELAP5 for system thermal-hydraulic calculations. Containment backpressure calculations are performed by an ICECON module within S-RELAP5.

Both the S-RELAP5 and RODEX3A computer codes are NRC-approved within the context of the RLBLOCA evaluation model. The ICECON module within the S-RELAP5 code is a variant on the CONTEMPT containment code series.

S-RELAP5 utilizes a two-fluid (plus non-condensibles) model with conservation equations for mass, energy, and momentum transfer. The reactor core is modeled with heat generation rates determined from reactor kinetics equations (point kinetics) with reactivity feedback, and with actinide and decay heating.

The two-fluid formulation uses a separate set of conservation equations and constitutive relations for each phase. The effects of one phase on another are accounted for by interfacial friction and heat and mass transfer interaction terms in the conservation equations. The conservation equations have the same form for each phase; only the constitutive relations and physical properties differ.

The modeling of plant components is performed by following guidelines developed to ensure accurate accounting for physical dimensions and the dominant phenomena expected during LBLOCA. The basic building blocks for modeling are the hydraulic volumes for fluid paths and the heat structures for heat transfer surfaces. In addition, special purpose components exist to represent specific components such as the pumps or the steam generator separators. Plant geometry is modeled at the resolution necessary to resolve the flow field and the phenomena being modeled within practical computational limitations.

A typical calculation for each of the “sampled” cases using S-RELAP5 begins with the establishment of a steady-state initial condition with all loops intact. The input parameters and initial conditions for this steady-state calculation are chosen to accommodate operation within plant Technical Specifications or plant-specific measured data. Following the establishment of an acceptable steady-state condition, the transient calculation is initiated by introducing a break in the cold leg of the loop with the pressurizer. The evolution of the transient through blowdown, refill, and reflood is computed continuously using S-RELAP5.

For containment modeling, an EM requirement is the confirmation of the 1.7 Uchida heat transfer coefficient multiplier for application to containment heat structures. If the confirmation is unsuccessful, the value of the Uchida multiplier is re-established following the process diagramed in Figure 3-1.

The methodology assumes a conservative single failure—the failure of a train of Emergency Core Cooling (ECC) pumped injection. Another train of ECC pumped injection is assumed to be out of service for maintenance. Hence, the analysis assumes only two of the four trains of pumped injection are functional.

The methods used in the application of S-RELAP5 to large break LOCA are fully described in Reference 1. A detailed assessment of this computer code was made through comparisons to experimental data. These assessments were used to develop quantitative estimates of the ability of the code to predict important physical phenomena in a PWR large break LOCA. The final step of the realistic LOCA methodology is to combine all the uncertainties related to the code and plant parameters, and estimate the PCT at 95 percent probability. The steps taken to derive the PCT uncertainty estimate are summarized below:

- Base Plant Input File Development

  First, base RODEX3A and S-RELAP5 input files for the plant (including the containment input file) are developed based on plant-specific information. Code input development guidelines are applied to ensure that the model nodalization is consistent with the model nodalization used in the code validation.

- Sampled Case Development

  The non-parametric statistical approach requires that many “sampled” cases be created and processed. For every set of input created, each “key LOCA parameter” is randomly sampled over a range established through code uncertainty assessment or expected operating limits (provided through plant

Technical Specifications, data, etc.). Those parameters considered "key LOCA parameters" are listed in Table 3-1. This list includes both parameters related to LOCA phenomena (based on the Phenomena Identification and Ranking Table (PIRT) provided in Reference 1) and parameters related to plant operation.

- Determination of Adequacy of ECCS

  The RLBLOCA methodology uses a non-parametric statistical approach to determine values of PCT, peak local oxidation, and total oxidation. The PCT is determined at a 95 percent probability level with 95 percent confidence. The peak local oxidation and total oxidation are reported for the limiting PCT case. The adequacy of the ECCS is demonstrated when the PCT satisfies the criterion set forth in 10CFR50.46.

Criteria in 10CFR50.46 also require assessment of the consequences of thermal and mechanical deformation of the fuel assemblies in the core during a LOCA. While AREVA's fuel designs minimize the potential for rod bowing, the effect of fuel rod bowing on whole-core blockage is considered. The minor adjustments of fuel pin pitch due to rod bowing do not alter the fuel assembly flow area substantially and the average sub-channel flow areas are preserved. Therefore, rod bow does not have a detrimental effect on LOCA mitigation. LOCA-seismic deformation of the fuel pin lattice is also considered. Deformations are expected to remain elastic and be confined to peripheral fuel assemblies. The U.S. EPR plant will be shown to meet the coolable geometry requirements of 10CFR50.46.

While addressing the coolable geometry requirements, long-term cooling also will be assessed to demonstrate compliance with the 10CFR50.46 criterion. Initial adequacy of the ECCS is shown by demonstrating that the core is quenched and the cladding temperature is returned to near saturation. Thereafter, long-term cooling is achieved by the pumped injection systems. These are redundant systems and provide a continuous flow of cooling water to the core fuel assemblies so long as the coolant channels in the core remain open. The concentration of boric acid within the core can induce a crystalline precipitation that may prevent coolant flow from reaching portions of the core. However, the U.S. EPR design provides for simultaneous hot and cold leg injection within approximately two hours of an event, thereby mitigating the boron precipitation issue. Long-term cooling will be shown to be acceptable for U.S. EPR plants.

The core for U.S. EPR plants will be composed of fuel assemblies having the same thermal-hydraulic characteristics; therefore, there are no mixed core considerations.

3.1 *Event Description*

The RLBLOCA EM was developed, and approved by the NRC, for the licensing analysis of large break LOCA transients per the requirements of 10CFR50.46. The methodology considers two break configurations: (1) double-ended guillotine breaks and (2) split breaks. Break configuration and size are sampled parameters. Guillotine breaks are ranged from two-area to one-area breaks and split breaks are ranged from one-area to 0.1-area breaks, where area refers to the pipe cross-sectional area. The evolution of a typical LBLOCA for the U. S. EPR plant is discussed in the following section.

3.2 *Large Break LOCA Scenario*

The Large Break LOCA event is defined in Section 15.6.5 of the U.S. Nuclear Regulatory Commission’s Standard Review Plan (SRP) (Reference 4) as follows:

"Loss-of-coolant accidents (LOCA) are postulated accidents that would result from the loss of reactor coolant, at a rate in excess of the capability of the normal reactor coolant makeup system, from piping breaks in the reactor coolant pressure boundary. The piping breaks are postulated to occur at various locations and include a spectrum of break sizes, up to a maximum pipe break equivalent in size to the double-ended rupture of the largest pipe in the reactor coolant pressure boundary. Loss of significant quantities of reactor coolant would prevent heat removal from the reactor core, unless the water is replenished.”

A LBLOCA is initiated by a postulated break in the RCS piping. Based on numerous industry studies, the limiting break location for current PWRs has been shown consistently to occur in the cold leg piping between the reactor coolant pump and the reactor vessel; nothing in the U.S. EPR design invalidates that conclusion. The plant is assumed to be operating normally at full power prior to the accident. A break in the cold leg piping, downstream from the pump, is assumed to open instantaneously. A rapid depressurization[1] of the primary system occurs, along with a core flow stagnation and reversal. RCS depressurization, together with the core flow stagnation and reversal, causes the fuel rods to experience DNB. Subsequently, the limiting fuel rods are cooled by film and transition boiling heat transfer. Coolant voiding creates a strong negative reactivity effect and core fission ends. As heat transfer from the fuel rods is reduced, cladding temperatures rise. A reactor trip signal is initiated when the low pressurizer pressure trip setpoint is reached. For RLBLOCA analyses, reactor trip is conservatively neglected. The reactor is rapidly shut down via core coolant voiding.

As a result of depressurization, coolant in all regions of the RCS begins to flash. At the break plane, the loss of subcooling results in substantially reduced break flow, which reduces the depressurization rate, and leads to a period of positive core flow or reduced downflow in the core as the reactor coolant pumps in the intact loops continue to supply water to the vessel. Cladding temperatures decrease and some portions of the core rewet during this period.

This positive core flow or reduced core downflow period ends as two-phase conditions occur in the reactor coolant pumps, thereby reducing their effectiveness. Once again, the core flow reverses as most of the vessel mass flows out of the primary system through the broken cold leg.

---

[1] Although the automatic partial cooldown system of the U.S. EPR is available to cool and depressurize the RCS, it is not modeled. Per the RLBLOCA EM, the steam generators are conservatively isolated at break initiation.

Mitigation of the LBLOCA begins when the SIS is actuated on very low pressurizer pressure. A worst single failure is assumed for ECCS safety analysis. This single failure is the loss of one ECCS pumped injection train, which equates to the loss of one MHSI pump and one LHSI pump. In addition, another train of MHSI and LHSI is assumed to be unavailable because of maintenance. This means both LHSI cross-connect lines are open. All four accumulators are available.

An on-time start and normal lineups of the containment spray, fan coolers (if present), or other cooling mechanisms are assumed in the EM. For the U.S. EPR plant, containment sprays are unavailable for a number of hours following LOCA initiation. Also, the U.S. EPR has no fan coolers. Hence, neither sprays nor fan coolers are present in the RLBLOCA model.

Cooling of the IRWST is performed by the LHSI pumps and associated heat exchangers. The LHSI pumps take suction from the IRWST and circulate a portion of the flow through minimum flow lines back to the IRWST. The minimum flow lines branch from the LHSI line downstream of the LHSI heat exchanger; thus, all LHSI flow is cooled by the LHSI heat exchanger, including flow through the minimum flow lines. Cooling of the IRWST will not significantly impact containment pressure during an RLBLOCA event.

When the RCS pressure falls below the accumulator pressure, fluid from the accumulators is discharged into the cold legs. In the early delivery of accumulator water, high pressure and high break flow will cause some of this fluid to bypass the core. During this bypass period, core heat transfer remains poor and fuel rod cladding temperatures increase. As RCS and containment pressures equilibrate, ECCS water begins to fill the lower plenum and eventually the lower portions of the core; thus, core heat transfer improves and cladding temperatures decrease. Eventually, the relatively large volume of accumulator water is exhausted and core recovery relies on pumped SI coolant delivery.

As the accumulators empty, the nitrogen gas used to pressurize the accumulators enters the RCS. Its release causes a short period of improved core heat transfer as the nitrogen gas displaces water in the downcomer. After the nitrogen gas is expelled through the break, the ECCS may temporarily be unable to sustain full core cooling because of the core decay heat and the higher steam temperatures created by quenching lower portions of the core. Fuel rod cladding temperatures increase for a short period until additional energy is removed from the core by low pressure safety injection, which is facilitated by continued decay heat reduction. Steam generated from fuel rod rewet entrains liquid and is carried around the loop before being vented out the break. The resistance of this flow path to the steam flow is balanced by the driving force of water filling the downcomer. It acts to retard the progression of core reflooding and postpones core-wide cooling.

Within minutes of accident initiation, core reflood progresses sufficiently to ensure core-wide cooling. Full core quench occurs within a few minutes after core-wide cooling. Long-term cooling is then sustained with low head safety injection.

3.3 *LOCA Acceptance Criteria*

A LBLOCA event is part of the LOCA definition in Section 15.6.5 of the U.S. Nuclear Regulatory Commission's SRP (Reference 4). It is classified as a postulated accident and a Condition IV event. It is not expected to occur during the lifetime of the plant; however, it is considered a design basis accident.

The LBLOCA acceptance criteria, as stated in 10CFR50.46, are:

- The calculated fuel element cladding temperature shall not exceed 2,200 °F.
- The calculated total oxidation of the cladding shall nowhere exceed 0.17 times the total cladding thickness before oxidation.
- The calculated total amount of hydrogen generated from the chemical reaction of the cladding with water or steam shall not exceed 0.01 times the hypothetical

amount that would be generated if all of the metal in the cladding cylinders surrounding the fuel, excluding the cladding surrounding the plenum region, were to react.

- Calculated changes in core geometry shall be such that the core remains amenable to cooling.

- After any calculated successful initial operation of the ECCS, the calculated core temperature shall be maintained at an acceptably low value and decay heat shall be removed for the extended period of time required by the long-lived radioactivity remaining in the core.

U.S. EPR LBLOCA licensing applications will meet all five criteria.

3.4 *Cases Analyzed*

The RLBLOCA EM defines an analysis as a case set comprising a minimum of 59 individual transient cases. Per the EM, all breaks are located at the pump discharge, the limiting location in the primary system. The values for the sampled parameters are chosen randomly for each transient case within a specified range based on plant operating limits and uncertainties.

3.5 *Choice of Single Failure and Preventive Maintenance*

The U.S. EPR design contains four SIS/RHRS trains of pumped injection each with its own diesel generator. Total pump capacity is such that the four-train configuration allows performance of preventative maintenance on one complete train during normal operation. Hence, in addition to the single failure loss of one complete SIS pumped injection train, a second train of pumped injection is assumed out of service for maintenance. Thus, for U.S. EPR RLBLOCA applications, only two trains of SIS injection are considered operational. One train is associated with the broken cold leg, the other with one of the three intact cold legs. As described in Section 2.2.2, the LHSI portions of the SIS have cross-connects which are open when a SIS/RHRS train is out of service for maintenance. The cross-connects connect Loops 1 and 2 and Loops 3 and 4. These connections ensure that at least one cold leg opposite the break provides LHSI flow to the downcomer. The intact cold leg with the active SIS is a sampled parameter in the RLBLOCA uncertainty analysis. The actual distribution of LHSI flow to the cold legs reflects the cross-connects and is determined dynamically by S-RELAP5 based on local fluid conditions. Because the cross-connects are upstream of the LHSI/MHSI junctions, only two cold legs (one broken and one intact) receive MHSI flow.

3.6 *Initial Conditions and Key Input Parameters*

The S-RELAP5 sample problem model presented in Appendix A is based on preliminary U.S. EPR design information. Nevertheless, the sample problem results provided in the Appendix are suitable for the intended purpose of illustrating expected plant LOCA performance using AREVA NP's NRC-approved RLBLOCA EM. Table 3-1 provides a list of the parameters sampled during the RLBLOCA analysis.

3.7 *Equipment Status*

Equipment status is presented in Table 3-2.

3.7.1 *Trips and Controls Credited in the RLBLOCA Analysis*

Under accident conditions, a reactor trip signal is generated when the pressurizer low pressure trip setpoint is reached; however, this trip is conservatively neglected in a RLBLOCA analysis and the reactor is shutdown by core coolant voiding. Control rod insertion is not credited. A pumped safety injection actuation signal is issued when the very low pressurizer pressure setpoint is reached; a maximum ECCS pumped injection delay time is assumed. (The U.S. EPR does not have a high containment pressure trip to actuate pumped safety injection.) Accumulators automatically begin discharge into the cold legs once the primary system pressures falls below their pressure. The partial SG secondary side cooldown system is conservatively not modeled for LBLOCA. The rapid depressurization of the primary system and steam generator isolation with break initiation preclude the need for its modeling.

The RLBLOCA EM samples LOOP, tripping the reactor coolant pumps at event initiation if LOOP is chosen. The U.S. EPR also utilizes a pump trip on low pump pressure difference (ΔP) in combination with an SIS actuation signal. If the safety injection actuation signal was generated and the pump ΔP falls below 75 percent of the ΔP across the pump in normal operations, then the main coolant pumps are tripped. Accordingly, if offsite power is available, the pump ΔP trip is modeled.

3.7.2 *Status of Key Plant Equipment*

The U.S. EPR has four complete safety trains with each train comprising an accumulator, MHSI and LHSI pumped injection, and a diesel generator. The MHSI and LHSI injection lines tee into the accumulator line which in turn connects to the cold leg piping downstream of the pump discharge. The LHSI has cross-connects that are opened when one safety train is down for maintenance. All four accumulators, passive devices, are functional. However, only two of the four trains of ECCS pumped injection are assumed to function; the single failure removes one train and a second train is assumed down for maintenance. Containment sprays, part of the severe accident heat removal system, are unavailable for actuation until some twelve hours after transient initiation and are not considered in the analysis.

Table 3-1 Sampled RLBLOCA Parameters

Phenomenological	
	Time in cycle (axial shape, rod properties, and burnup)
	Peaking factors
	Break type (guillotine versus split)
	Break size
	Critical flow discharge coefficients (break)
	Offsite power availability
	Decay heat
	Critical flow discharge coefficients (surgeline)
	Initial upper head temperature
	Film boiling heat transfer
	Dispersed film boiling heat transfer
	Critical heat flux
	T_{min} (intersection of film and transition boiling)
	Initial stored energy
	Downcomer hot wall effects
	Steam generator interfacial drag
	Condensation interphase heat transfer
	Metal-water reaction
Plant[2]	
	Core power
	Initial flow rate
	Initial operating temperature
	Pressurizer pressure
	Pressurizer level
	Containment volume
	Containment temperature
	Accumulator pressure
	Accumulator system volume
	Intact cold leg with operational MHSI and LHSI

[2] Uncertainties for plant parameters are based on plant-specific data.

Table 3-2: Equipment Status

Plant Equipment or System	Status
SIS Actuation	SIS actuation is on the very low pressurizer pressure setpoint, 1667.9 psia (with an uncertainty of ± 25 psi for normal conditions and ± 55 psi for degraded conditions).
MHSI and LHSI	• One train out of service for preventive maintenance • One train out of service due to single failure • One MHSI pumps to the broken cold leg. One LHSI pumps to the broken cold leg and one intact leg through a cross-connection. • One MHSI pumps to one of the intact cold legs (sampled). One LHSI pumps to one of the intact cold legs (sampled – same cold leg receiving MHSI) and to another cold leg through a cross-connection.
Accumulators	All four accumulators are available.
Control Rod Scram	Rod insertion is not credited.
Reactor Coolant Pumps	The RCPs trip on LOOP or “on low ΔP over RCP and SIS signal,” where the minimum ΔP over the RCP setpoint is defined as 75 percent of the nominal ΔP.
Partial Cooldown	Per the RLBLOCA EM, SG isolation occurs at break initiation; hence partial cooldown is not simulated.
Steam Generator Main Steam and Feedwater	Per the RLBLOCA EM, SG isolation occurs at break initiation.

Figure 3-1: Uchida Multiplier Benchmark Flow Diagram

4.0 U.S. EPR LARGE BREAK PHENOMENA

The RLBLOCA EM was developed following the CSAU approach (Reference 3). A PIRT process was used to identify and rank key phenomena for each of the three phases—blowdown, refill and reflood—of a large break LOCA transient (Reference 1, Table 3.4). The most important phenomena (ranking seven or higher), grouped by transient phase, are discussed in the following three sections, concluding that the U.S. EPR design would not change the outcome of the PIRT.

4.1 *Blowdown Phenomena*

- Fuel Rod Stored Energy: U.S. EPR fuel is the same, excepting active core length, as that used in current PWR plants analyzed by the RLBLOCA methodology. The longer core length is within the calculation capabilities of the codes (RODEX3A and S-RELAP5) and methodology to analyze, so the model parameters (see Table 4.19 in Reference 2) required in all RLBLOCA analyses are also applicable to the U.S. EPR. The U.S. EPR design introduces no new methodological or phenomenological considerations with respect to fuel rod stored energy.

- Core Departure from Nucleate Boiling (DNB): DNB is modeled in S-RELAP5 by the Biasi and modified Zuber Critical Heat Flux (CHF) correlations. The calculations are conservatively biased using a multiplier, and sensitivity studies concluded that DNB is not significant to LBLOCA PCT (see Table 4.1 in Reference 1). Hence, the correlations and multiplier are equally applicable to the U.S. EPR. Further evidence of U.S. EPR applicability is shown in Appendix A, Table A-9, a plant-specific check for RLBLOCA core heat transfer range applicability. The U.S. EPR design introduces no new methodological or phenomenological considerations with respect to core DNB.

- Core Post-CHF Heat Transfer: Core post-CHF heat transfer was assessed by comparing THTF test data with S-RELAP5 (Reference 1, Sections 4.3.1.1 and 4.3.3.2.5). The results defined uncertainty ranges used in the RLBLOCA methodology. Those same ranges are equally applicable to U.S. EPR calculations. There is nothing unique about the U.S. EPR design that would change or invalidate the Oak Ridge National Laboratory Thermal-Hydraulic Test Facility (THTF) benchmark. Again note the comparisons presented in Appendix A, Table A-9. The U.S. EPR design introduces no new methodological or phenomenological considerations with respect to core post-CHF heat transfer.

- Rewet: S-RELAP5 benchmarks of test data exhibiting blowdown rewetting (Reference 1, Section 4.3.2.1.4) conservatively predicted the measured PCTs. Rewetting was not predicted everywhere it was observed; but the calculated clad temperatures followed the data trends, and the predicted PCT was 1350 °F compared to the measured PCT of 1236 °F. The U.S. EPR introduces no new methodology or phenomenological considerations with respect to blowdown rewet (quench).

- The phenomenon of blowdown rewet (quench) is discussed further in Appendix A, Section A.3.0, as part of the LBLOCA sample calculations.

- Core Flow Reversal and Stagnation: Core flow reversal and stagnation are the result of break size and the rate of coolant loss versus the rate of coolant injection from the ECC systems. The methodology treats these items by ranging associated parameters such as break size, break coefficient, break type, RPV upper head temperature, and accumulator pressure, volume and temperature (Reference 1, Section 4.3.3.1.3). For the U.S. EPR, ranging of these parameters is still appropriate; the plant configuration presents no unique features in that regard. The U.S. EPR design introduces no new methodological or phenomenological considerations with respect to core flow reversal and stagnation.

- Critical Flow at the Break: Critical flow at the break was assessed by comparison of S-RELAP5 with full-scale critical flow tests at the Marviken facility (Reference 1, Section 4.3.3.2.7). S-RELAP5 code predictions agreed well with the test data (Reference 1, Figure 4.99). Moreover, the U.S. EPR break geometry and fluid conditions are similar to those of current PWRs for which the RLBLOCA methodology applies. Hence, S-RELAP5 is capable of calculating critical flow; and the critical flow uncertainty parameters described in Reference 1 are also applicable to U.S. EPR.

- Flow Split Between Loops: The flow split between loops is controlled in the methodology by independently ranging the discharge coefficients of the two broken ends of the cold leg pipe in the RLBLOCA uncertainty analysis (Reference 1, Section 4.3.3.2.7). Ranging as specified in the methodology will be applied to the U.S. EPR. Therefore, the code and methodology are also applicable to the U.S. EPR.

4.2 *Refill Phenomena*

- Core Post-CHF Heat Transfer: Core post-CHF heat transfer was assessed by comparing THTF, FLECHT and FLECHT-SEASET test data with S-RELAP5 predictions (Reference 1, Sections 4.3.1.1 and 4.3.3.2.5). The results defined uncertainty ranges used in the RLBLOCA methodology. Those ranges are equally applicable to U.S. EPR calculations. There is nothing unique about the U.S. EPR design that would change or invalidate the above mentioned benchmarks. Note the comparisons presented in Appendix A, Table A-9, for further evidence of applicability. The U.S. EPR design introduces no new methodological or phenomenological considerations with respect to core post-CHF heat transfer.

- Cold Leg Condensation and Oscillations due to Accumulator Injection: Cold leg condensation and oscillations due to accumulator injection are discussed in Section 5.2. It was concluded that, since the U.S. EPR will conform to the noding configuration guidelines, the results and conclusions of the EM relative to this issue are applicable to the U.S. EPR.

- Accumulator Discharge: Accumulator differences relative to current plants are also discussed in Section 5.2. It was determined that any such differences are inconsequential regarding EM applicability to the U.S. EPR plant.

- Downcomer Entrainment/De-entrainment and Countercurrent, Slug and Non-equilibrium Flow: The radial width and hydraulic diameter of the lower downcomer region are somewhat larger than current 4-loop plants. Both small-scale (LOFT and Semi-Scale) and full-scale (UPTF) data were used to evaluate ECC water penetration into the downcomer. The tests demonstrate that, with the RLBLOCA methodology plant lower plenum nodalization, the code conservatively predicted the entrainment of ECC water from the intact cold legs to the broken cold leg during the cold-leg filling period, and correctly predicted full or partial entrainment of ECC water to the broken cold leg during the lower plenum refill period (Reference 1, Section 4.3.1.11.1). Due to the use of both small-scale and full-scale data, the effects of scale were taken into account in evaluating downcomer entrainment effects predicted by S-RELAP5 as it will be applied for the U.S. EPR. Therefore, the evaluations are also applicable to U.S. EPR plants.

- Downcomer Condensation: A wide range of downcomer condensation rates were used to evaluate S-RELAP5 for the RLBLOCA methodology. With the plant nodalization used in the RLBLOCA EM S-RELAP5 plant model, downcomer penetration of ECC water is conservatively predicted. The interfacial condensation heat transfer coefficient applied in the cold legs and downcomer is a parameter that is varied in the RLBLOCA uncertainty analysis (Reference 1, Table 4.19). The U.S. EPR analyses will conform to the nodalization specified in the methodology; thus, the conclusions for current PWRs are also applicable for the U.S. EPR.

- Downcomer 3-D Effects: Downcomer 3-D effects were evaluated by comparison of S-RELAP5 to the Upper Plenum Test Facility (UPTF) tests

(Reference 1, Section 4.3.1.11). Results of those tests indicated that S-RELAP5 can calculate the 3-D effects, and that refilling of the downcomer is conservatively predicted. The codes and methodology are also capable of modeling the phenomenon for the U.S. EPR.

- Loop Flow Oscillations: Comparisons of S-RELAP5 to UPTF Test 8 demonstrated that S-RELAP5 is capable of calculating the appropriate phenomena in a full-scale facility (Reference 1, Section 4.4.2.2.8). There is nothing unique about the U.S. EPR design that would change or invalidate the above mentioned benchmark. Thus, the codes and methodology are also capable of modeling the phenomena for the U.S. EPR.

- Flow Split Between Loops: Flow split between the loops is controlled in the methodology by independently ranging the discharge coefficients of the two broken ends of the cold leg pipe in the RLBLOCA uncertainty analysis (Reference 1, Section 4.3.3.2.7). Ranging as specified in the methodology will be applied to the U.S. EPR. Therefore, the code and methodology are also applicable to the U.S. EPR.

4.3 *Reflood Phenomena*

- Fuel Rod Oxidation: Fuel parameters affecting fuel rod oxidation are the same for the U.S. EPR as for the applicable current PWRs.

- Fuel Rod Decay Heat: Fuel parameters affecting fuel rod decay heat are the same for the U.S. EPR as for the applicable current PWRs.

- Core Post-CHF: Core Post-CHF was assessed by comparing THTF and FLECHT-SEASET test data with S-RELAP5. The results defined uncertainty ranges used in the RLBLOCA methodology (Reference 1, Section 4.3.3.2.5). Those same ranges will be applied to U.S. EPR calculations. Thus, the Post-CHF model is applicable to the U.S. EPR. Refer to Appendix A, Table A-9, for further validation.

- Core Reflood Heat Transfer and Quench: During reflood, S-RELAP5 maps the appropriate reflood heat transfer regime along the axis of the core. This model was assessed as a best-estimate model against both separate effects and integral effects tests, including FLECHT-SEASET, CCTF, SCTF, LOFT and Semi-Scale. The results of those evaluations demonstrated that the models for the phenomena used in S-RELAP5 can be applied to full-scale PWR LBLOCA events (Reference 1, Section 4.4.2.1).

  Core quenching is no different for the U.S. EPR than for applicable PWRs. The S-RELAP5 model is conservatively biased in sampling of the heat transfer coefficients. Those models will be applied to the U.S. EPR consistent with their application in current PWRs. (Refer to Table A-9.)

  Therefore, the code and methodology are capable of modeling the phenomena for the U.S. EPR.

- Core 3-D Flow, Void Distribution and Generation: Code assessments demonstrated best-estimate performance of S-RELAP5 for core 3-D flow, void distribution and generation (Reference 1, Section 4.3.3.1.1). Core 3-D effects are influenced by the initial power distributions and the size of the break. Power distributions and break size, type and discharge coefficient are randomly varied in the RLBLOCA uncertainty analysis—as they will be for the U.S. EPR. The codes and methodology are both capable of modeling the phenomena for the U.S. EPR.

- Core Entrainment/De-entrainment: Reference 1, Section 4.3.3.1.2, notes that liquid entrainment in the core was demonstrated to be conservatively calculated by the S-RELAP5 code. As noted in Reference 1, Section 4.4.2.2.2, the determinants of the model applicability to PWR LBLOCA events for models affecting core entrainment are primarily local and, in the core, are principally related to the conditions within the flow channel between the fuel rods. The U.S. EPR flow channels are within the range of plant types applicable to the

RLBLOCA methodology. The tests used in assessing core entrainment used full-length (twelve foot) fuel rods, and comparisons of S-RELAP5 to the data demonstrated that the core entrainment model in S-RELAP5 is conservative and scales suitably to full-scale PWR LBLOCA events. Since the U.S. EPR will conform to the nodalization and modeling specified in the methodology, the codes and methodology are capable of modeling the phenomena for the U.S. EPR.

- Upper Plenum Entrainment/De-entrainment: Comparison of S-RELAP5 to test data demonstrated that liquid level in the upper plenum is generally over predicted by S-RELAP5 for reflood conditions (Reference 1, Section 4.3.3.1.2). As a result, S-RELAP5 conservatively models carry-over. Since the upper plenum of the U.S. EPR is within the range of applicable plant types, and the U.S. EPR will conform to the approach and modeling prescribed in the methodology, it is concluded that S-RELAP5 and the methodology are also capable of calculating the phenomena for the U.S. EPR.

- Upper Plenum Draining and Fall-Back: As noted above, S-RELAP5 generally over predicts the liquid level in the upper plenum, thereby demonstrating that the code does not allow too much liquid to fall-back into the core. Also, the methodology conservatively disallows radial cross-flow in the first axial level of the upper plenum above the hot assembly, creating a virtual standpipe that restricts fall-back into the hot assembly. Since the U.S. EPR will conform to the approach and modeling prescribed in the methodology, it is concluded that S-RELAP5 and the methodology are also capable of calculating the phenomena for the U.S. EPR.

- Steam Generator Steam Binding: Containment pressure during a LBLOCA is generally higher for the U.S. EPR than for current PWR plants. A major impact of higher containment pressure is that it will tend to reduce steam binding in the steam generators due to higher steam density. As shown in the PIRT, steam binding has a relatively strong impact during the reflood phase; and reducing steam binding tends to reduce PCT.

High steam generator operating pressure and temperature tend to increase steam binding. This phenomenon was shown to be conservatively predicted by S-RELAP5 (Reference 1, Section 4.3.1.11.3), and those tendencies will be the same for the U.S. EPR as they are for current PWRs. Moreover, the U.S. EPR response is conservatively modeled because the SG partial cooldown feature is not credited.

Due to the conservative range of variation in containment pressure and conservative modeling in the methodology and codes, steam binding is conservatively biased in the RLBLOCA methodology and codes as they are applied for current PWRs and as they will be applied to the U.S. EPR.

- RCP Differential Pressure Form Loss: U.S. EPR pump-specific homologous curves will be used in accordance with the methodology specifications. Thus, the code and methodology are both applicable to the U.S. EPR.

- Non-condensable Gas: Modeling of the U.S. EPR accumulators will conform to the methodology requirements. As noted in Section 5.2, the nitrogen pressurization of the U.S. EPR accumulators is within the range of applicability to current PWRs. Thus, the S-RELAP5 code and methodology are equally capable of calculating the non-condensable gas effects for the U.S. EPR.

- Accumulator Discharge: Accumulator differences are discussed in Section 5.2.

- Downcomer Liquid Level Oscillations: Downcomer liquid level oscillation is a phenomenon that is controlled primarily by other phenomena (Reference 1, Section 4.3.3.1.11). The ranging of these phenomena either will or will not produce the oscillations based on their ranging. Manometer type downcomer liquid level oscillations have not been observed to any significant extent in the methodology nodalization models. The lack of these oscillations is conservative because the effect of the oscillations is to drive water up into the core and provide an additional cooling mechanism. Thus, the S-RELAP5 code and methodology representation of this phenomenon is acceptable for the U.S. EPR.

- Loop Flow Oscillations: Comparisons of S-RELAP5 to UPTF Test 8 demonstrated that S-RELAP5 is capable of calculating the appropriate phenomena in a full-scale facility (Reference 1, Section 4.4.2.2.8). Thus, the codes and methodology are also capable of modeling the phenomena for U.S. EPR.

Based on the above considerations, it is concluded that the existing RLBLOCA methodology is suitable for simulating the various phenomena that occur during a large break transient as it will be analyzed for the U.S. EPR. The U.S. EPR design introduces no new phenomenological considerations that would require RLBLOCA EM modifications.

5.0 S-RELAP5 CODE VALIDATION FOR U.S. EPR LARGE BREAK LOCA ANALYSES

This section covers validation of the RLBLOCA S-RELAP5-based EM for application to the U.S. EPR. It is concluded that the U.S. EPR contains no design features or transient phenomena requiring additional benchmarks or methodology changes.

5.1 *S-RELAP5 Acceptance for LBLOCA Analysis*

Table 5-1 summarizes the benchmarks used to assess or otherwise assure that S-RELAP5 adequately simulates the important LBLOCA phenomena discussed in Section 4. No additional benchmarks are required to demonstrate U.S. EPR applicability.

5.2 *S-RELAP5 Acceptability for U.S. EPR LBLOCA Analysis*

This section discusses design differences between the U.S. EPR and current PWR plants that are relevant to Chapter 15 RLBLOCA safety analyses. Disposition arguments that justify the applicability of the RLBLOCA methodology to the U.S. EPR are provided for those differences that could potentially have a significant impact on the valid application of the codes, model, or other aspects of the EM.

- <u>High Containment Pressure</u>: For large break LOCA, the U.S. EPR transient containment pressure is expected to be higher than in current plants. This is because the U.S. EPR does not have fan coolers, and containment sprays (reserved for severe accidents) are not activated until approximately twelve hours after transient initiation. Containment pressure is a significant PIRT-identified factor during refill and reflood. The methodology treats containment pressure as a statistically varied parameter by randomly sampling containment volume. The magnitude of the pressure does not require ICECON or other methodology changes. The RLBLOCA EM is adequate and appropriate. The higher U.S. EPR containment pressures are within the S-RELAP5 (ICECON module) code and methodology modeling capabilities.

- Containment Heat Removal System: As noted previously, the U.S. EPR containment design does not have fan coolers; nor does it activate containment sprays for LBLOCA. Though lack of containment spray in the ICECON calculations differs from the RLBLOCA analyses for most PWRs, it is within the code modeling capabilities; and it is within the methodology. No ICECON or other methodology changes are required; the RLBLOCA EM remains applicable.

- In-containment Refueling Water Storage Tank: The IRWST is essentially an open pool within the containment building, which partly immerses a portion of the containment building structure. The open pool covers about two-thirds of the floor area at the bottom of the containment building. The IRWST functions as both the external water storage tanks and internal sumps of current PWRs. Additionally, there is a heat exchanger downstream of the LHSI pump that provides safety grade cooling of the LHSI for the SIS. There is also a minimum flow line downstream of the heat exchanger that flows back to the IRWST and provides cooling of the IRWST, including during LOCA events.

  Being inside the containment, the IRWST water temperature variation is basically the same as normal operational containment temperature, about 60 °F to 120 °F. The RLBLOCA methodology requires the tank water temperature for pumped safety injection to be set equal to the Technical Specification maximum value. Conforming to that requirement, the energy contained within the total RCS liquid mass in the primary system after depressurization will be mixed with the IRWST water, using the Technical Specification maximum IRWST water temperature. This approach results in a conservatively elevated temperature for the pumped SIS water, above the technical specification maximum IRWST temperature. LHSI heat exchanger cooling is conservatively neglected. The outlined procedure provides a means of determining a maximum IRWST water temperature in compliance with EM requirements.

The RLBLOCA methodology also stipulates that containment cooling supplied by the IRWST not be modeled with the same initial temperature assumed for safety injection. For the U.S. EPR, which does not make use of sprays, this essentially relates to the heat transfer between the containment atmosphere and the IRWST water. For that calculation, cooled LHSI flow re-circulated back to the IRWST is neglected. To the time of PCT, the amount of re-circulation flow is negligible relative to the volume of fluid in the IRWST. Summarizing with regards to the IRSWT, the RLBLOCA EM is capable of acceptably modeling the U.S. EPR configuration without change.

- MHSI: Unlike current PWRs, the U.S. EPR design uses MHSI pumps instead of HHSI pumps. While a difference between U.S. EPR and current 4-loop plants, the RLBLOCA EM is capable of modeling this configuration of ECC pumped injection without change.

- SIS/RHRS: The SIS/RHRS has four trains; and as long as all four trains are available, they are independent. If one train is down for maintenance, piping cross-connects are opened between Loops 1 and 2 and Loops 3 and 4, providing multiple injection points for the LHSI. Assuming a single failure and preventive maintenance, the U.S. EPR has two remaining SIS/RHRS trains for pumped injection. One train injects into the broken cold leg and into an intact cold leg through a cross-connect; and the second train injects into an intact cold leg (sampled) and into another cold leg (which could be the broken leg) through a cross-connect. This configuration results in pumped injection into the cold leg(s) opposite the break and is similar to current PWR designs for which the RLBLOCA EM has been used. Therefore, the RLBLOCA EM is capable of modeling SIS pumped injection for the U.S. EPR.

- Accumulators: U.S. EPR accumulators are configured similar to those in current plants. Their construct is such that they are not subject to a single failure nor are they allowed out of service for preventive maintenance. Thus, all four accumulators are available for accident mitigation. Their large capacity leads to a faster reactor vessel refill and higher flooding rates—all favorable trends which minimize the PCT.

S-RELAP5 was benchmarked against ACHILLES tests and shown not to over-predict the nitrogen-induced surge of water into the core and its resulting core cooling (Reference 1, Section 4.3.1.4). The tests demonstrate that the effects of nitrogen transport, including that occurring in the U.S. EPR, will be adequately predicted by S-RELAP5.

Condensation, due to ECCS injection into the cold legs, is also an important refill and reflood phenomenon. It was found to be appropriately treated by S-RELAP5 and the RLBLOCA methodology in benchmarks of the Westinghouse/EPRI 1/3-scale tests by using the cold leg nodalization specified by the methodology and the bias and uncertainty range of the interfacial condensation heat transfer coefficient in the ECC/steam mixing process (Reference 1, Section 4.3.3.2.9). Pressure and fluid oscillations in the loops caused by ECC injection into the cold legs were evaluated via the full-scale UPTF Test 8 (Reference 1, Section 4.4.2.2.8). Since the U.S. EPR will conform to the nodalization guidelines specified in the methodology, the range of tests from part-scale to full-scale demonstrate that the results and conclusions are applicable to the U.S. EPR. The features of the U.S. EPR accumulators can be modeled appropriately using the RLBLOCA EM without modification.

- <u>Preventive Maintenance</u>: The ramifications of preventive maintenance were previously discussed in SIS/RHRS and Accumulator items as well as in Section 3.5. It was concluded that the preventive maintenance impact on equipment operation was within the modeling and calculation capabilities of the RLBLOCA EM.

- <u>Large Primary System Component Sizing</u>: The larger (relative to current 4-loop plants) size of the U.S. EPR RCS and primary system components can affect the time to empty the pressurizer, the end of blowdown time, and the core bypass time. The sizing of U.S. EPR components is included in the S-RELAP5 model.

The larger RV downcomer was previously discussed in Section 4.2 and its scale found to be properly accounted for in the RLBLOCA EM. The U.S. EPR pressurizer volume relative to total RCS volume is larger than for current PWRs. This results in differences in the time to empty the pressurizer. However, the larger U.S. EPR pressurizer volume is included in the S-RELAP5 model and the code is fully capable of predicting differences in event timing.

Thus, the effects of larger components are within the capabilities of the methodology and codes to analyze.

- Large Reactor Vessel Free Volume between the Vessel Nozzles and Top of Active Core: The added distance between the top of the active core and the RV nozzles relative to current PWRs provides a taller head for core reflooding during LBLOCA events. The S-RELAP5 model reflects the difference in core elevation relative to the vessel nozzle. This difference, relative to current plants, will not produce conditions that are outside the capability of the methodology and codes to analyze.

- Heavy Reflector: The U.S. EPR differs from current PWRs in that it uses a heavy reflector—an all stainless steel structure between the multi-cornered periphery of the core and the core barrel. It effectively takes the place of the core baffle and eliminates the need for a thermal shield or neutron pads. The location of the metal mass differs from thermal shields or neutron pads in that it is located inside the core barrel, rather than outside the core barrel in the downcomer. The metal mass and volume of the heavy reflector are modeled in S-RELAP5. The location of the larger metal mass between the core and core barrel relative to the core baffle is a plant-specific difference that is not significant to the LBLOCA event. Flow through the axial cooling holes that are used to cool the heavy reflector are included in the bypass flow modeled in

S-RELAP5. These differences, while requiring minor noding changes relative to the noding for the current core baffle arrangement, are within the capability of the methodology and codes to analyze.

- Long Core: The RLBLOCA methodology does not impose limits on core height. To accommodate the 14-foot U.S. EPR core and preserve the level of detail in core modeling, the number of axial nodes was increased.

  The scalability of the RLBLOCA methodology (and the ability to model cores of different lengths) has been demonstrated by comparison of S-RELAP5 to experiments of different scales. These experiments include those performed in the Semiscale (1/1600 scale), LOFT (1/50 scale), CCTF (1/21 scale), and UPTF (1/1 scale) facilities. The scaling indicated for each facility is relative to a 4-loop plant. The facilities have core lengths ranging from 5.5 feet for LOFT and Semiscale to 12 feet for CCTF. The experiments covered all three phases of the LBLOCA: blowdown, refill, and reflood. The Semiscale and LOFT experiments covered all three phases while the CCTF covered the reflood and to a lesser extent the refill phases and the UPTF primarily addressed the refill phase. The good agreement between the experimental data and the calculation results for all of these different facilities demonstrate that the methodology is scalable.

  The experiments discussed above have a range of core heights that differ by over a factor of 2. The 14 foot core represents only a small increase in core height (approximately 17%) relative to the 12 foot core included in the methodology assessments. Thus, the approved methodology is judged to be applicable to 14 foot cores.

- Fuel Rod Lower Plenum and Isolation Pellet: U.S. EPR fuel rods include a lower plenum without a plenum spring and a non-fuel isolation pellet that separate the active fuel pellets from the lower plenum. The RODEX3A code and RLBLOCA model include the capability of modeling the U.S. EPR fuel rod lower plenum without modification. The isolation pellet has no effect on the RODEX3A modeling of the fuel rod. Therefore, the fuel rod is within the capability of the methodology and codes to analyze properly.

- Partial Cooldown: The U.S. EPR partial cooldown system is designed to cool the primary system and, thereby, lower the RCS pressure during various events, including LOCA. Current U.S. PWRs do not have a partial cooldown system. The U.S. EPR partial cooldown system is available during LOCA events, but it is not modeled in a RLBLOCA analysis. The RLBLOCA methodology requires steam generator isolation coincident with break initiation, rendering modeling of the partial cooldown system unnecessary. Furthermore, the partial cooldown system is unimportant during a large break LOCA due to the rapid depressurization of the RCS.

- Steam Generators Axial Economizer: U.S. EPR axial economizer steam generators differ from that of current U.S. 4-loop plants. The U.S. EPR design (shown in Figure A-2) physically separates the lower half of the downcomer into a cold half and a hot half. Feedwater is injected into only the cold half of the downcomer, while about 90 percent of the hot re-circulation fluid is deposited into the hot half of the downcomer. The hot and cold division is continued up through most (about two-thirds) of the tube region. Separators and dryers are also somewhat different in size and location than in current U.S. plants. While noding changes are necessary to represent the U.S. EPR steam generator configuration properly, no differences introduce hardware, phenomena or range of applicability issues not previously assessed during the development of the RLBLOCA methodology. The LBLOCA is insensitive to the treatment of the steam generators. The axial economizer and other steam generator design details are within the capabilities of the methodology to model and its codes to analyze.

- High Steam Generator Operating Pressure and Temperature: The U.S. EPR steam generators operate at higher pressure and temperature than typical PWRs. The higher steam generator operating pressures and temperatures tend to increase steam binding during reflood. As noted in Section 4.3, this difference is within the capability of the methodology and codes to analyze.

- RCP Trip - "RCP Trip on Low ΔP Over RCP and SIS signal": The RLBLOCA methodology statistically samples loss of offsite power, tripping the RCPs at event initiation for LOOP, but not tripping pumps if offsite power is available. For the U.S. EPR, the "RCP Trip on Low ΔP Over RCP and SIS signal" (see Table 3-2) is applied in the RLBLOCA uncertainty analysis cases, when offsite power is available. It would be non-conservative to continue supplying forced RCS flow. While a unique U.S. EPR feature, the trip occurs early in the event and presents no challenging or new analysis features. Thus, this trip is a plant-specific difference that is within the capability of the methodology and codes to model and analyze.

- Lack of SIS Initiation Trip on High Containment Pressure: Current U.S. PWRs typically have both high containment pressure and low pressurizer pressure trips to initiate SIS. Generally, the high containment pressure trip is first to actuate (usually within about one second after transient initiation) during LBLOCA. The U.S. EPR design does not have a high containment pressure trip. The RLBLOCA methodology provides for SIS initiation on either high containment pressure or low pressurizer pressure. For the U.S. EPR, the SIS is initiated on low pressurizer pressure (see Table 3-2). The delayed (several seconds relative to a high containment pressure trip) SIS initiation has no significant effect on RLBLOCA cases with or without LOOP. This is a plant-specific difference that is within the capability of the RLBLOCA methodology and codes to analyze.

Table 5-1: Assessment Matrix Tests and Phenomena Addressed

Table 5-1: Assessment Matrix Tests and Phenomena Addressed (continued)

6.0 CONCLUSIONS

The U.S. EPR plant was evaluated from a phenomenological viewpoint in Section 4 and from a design viewpoint in Section 5. The Section 4 review concluded that the U.S. EPR response during a LBLOCA involves no additional phenomena beyond those already considered by the existing RLBLOCA EM methodology (Reference 1). Moreover, the ranges of fluid conditions encountered are similar to those for current U.S. PWR plants and within the range of applicability of the EM methodology.

The Section 5 review identified design differences between the U.S. EPR and current U.S. PWR plants. It was concluded that the features of the U.S. EPR can be acceptably modeled and analyzed using the existing RLBLOCA EM.

In summary, the NRC-approved RLBLOCA EM is applicable without modification to the U.S. EPR plant.

7.0 REFERENCES

1. "Realistic Large Break LOCA Methodology for Pressurized Water Reactors," EMF-2103(P)(A) Revision 0, FANP Richland, Inc., April 2003.

2. "Codes and Methods Applicability Report for the U.S. EPR," ANP-10236P, Revision 0, August 2006.

3. Technical Program Group, "Quantifying Reactor Safety Margins," NUREG/CR-5249, EGG-2552, December 1989.

4. "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," NUREG-0800, LWR edition, Revision 2, U.S. Nuclear Regulatory Commission, July 1987.

APPENDIX A

LARGE BREAK LOCA SAMPLE CALCULATIONS

APPENDIX A

TABLE OF CONTENTS

Page

List of Tables

List of Figures

A.1.0 *Introduction and Summary*

The purpose of this appendix is to describe the structure and implementation of an S-RELAP5-based large break LOCA plant model, termed a sample problem. It is based on AREVA NP's NRC-approved RLBLOCA evaluation model (Reference A-1). Accident behavior reported in this appendix is representative of the U.S. EPR final design analyzed under LBLOCA conditions. However, since the design is subject to modest changes until the time of DCD submittal, the analysis of record will be that in the DCD.

Sections 3 through 6 describe the RLBLOCA methodology and codes, a generalized large break LOCA scenario, and justify the application of the RLBLOCA EM without modification to a U.S. EPR plant. The following summarizes the application of the RLBLOCA methodology to the U.S. EPR and the results of that application.

A.2.0 *Application Analysis Results*

The U.S. EPR is a 4-loop plant with U-tube steam generators, similar in most facets to the current generation of 4-loop PWR plants. It is designed to operate at a core thermal power of 4,590 MWt. The steam generators include an axial economizer for optimum thermal efficiency. The plant contains four safety trains. Each train contains its own MHSI and LHSI pumps and diesel generator. Per pump injection rates are provided in Tables A-1 and A-2. Diesel start time is set consistent with the loss-of-offsite-power assumption for ECCS pumped injection. The core is composed of 241, 17 x 17, thermal-hydraulically compatible fuel assemblies, containing UO_2 as well as 2, 4, and 8 weight percent gadolinia. The fuel rods and grids use AREVA NP's advanced M5® material. The active core is slightly less than 14 feet. The plant is bottom reflooded. The containment is a high pressure, double-walled, cylindrical vessel with a domed head.

The S-RELAP5 RLBLOCA plant model specifically represents the reactor vessel with internals and core, hot and cold leg primary system piping, main reactor coolant pumps, pressurizer and pressurizer surge line, steam generator primary and secondary sides, and ECCS (both pumped injection and accumulators). For the containment heat structures, the base RLBLOCA EM 1.7 Uchida heat transfer coefficient multiplier is used.[1] The tube plugging is a uniform 5 percent in all four steam generators. The analysis is for an equilibrium 18 month fuel cycle. Table A-3 lists many of the important modeling parameters.

The S-RELAP5 EPR plant model system nodalization details are shown in Figures A-1 through A-6. The model configuration is essentially the same as the 4-loop sample problem provided in Reference A-1 with changes incorporated to reflect current modeling guidelines and U.S. EPR specific hardware, e.g., the axial economizer steam generator design. Noding changes are addressed in Table A-4, Item 10, as part of the RLBLOCA EM SER compliance.

As described in the RLBLOCA methodology, many parameters associated with LBLOCA phenomenological uncertainties and plant operation ranges are sampled. Table A-5 presents process parameters and statistical distributions used in the analyses. The LBLOCA phenomenological uncertainties are provided in Reference A-1.

For the AREVA NP RLBLOCA evaluation model, significant containment parameters, as well as NSSS parameters, were established via a PIRT process. Other model inputs are generally taken as nominal or conservatively biased. The PIRT outcome yielded two important (relative to PCT) containment parameters—containment pressure and temperature. In many instances, the conservative guidance of CSB 6-1 (Reference A-2) was used in setting the remainder of the containment model input parameters. As noted in Table A-5, containment temperature is a sampled parameter. Containment pressure is indirectly ranged by sampling the containment volume.

The limiting PCT case (1,425 °F) is Case 44. It is characterized in Tables A-6 and A-7. The maximum oxidation (0.235 %) and total oxidation (< 0.01 %) results are also reported in Table A-7. The fraction of total hydrogen generated is not directly calculated; however, it is conservatively bounded by the calculated total percent oxidation that is well below the 1 percent limit. A nominal 50/50 PCT case was

[1] For U.S. EPR licensing applications such as the DCD, the 1.7 Uchida multiplier will be confirmed or reestablished via the benchmarking process described in Section 4.1.

identified as Case 33. The nominal PCT is 1,127 °F. This result can be used to quantify the relative conservatism in the limiting PCT case result. In this analysis, it is 298 °F.

The hot fuel rod results, event times and analysis plots for the limiting PCT case are shown in Table A-7, Table A-8, and in Figures A-7 through A-21, respectively. Figure A-7 shows linear scatter plots of the important parameters sampled for the 59 calculations. These figures show the parameter ranges used in the analysis. Figures A-8 and A-9 show PCT scatter plots versus the time of PCT and versus break size for the case set. Figure A-10 shows the maximum oxidation versus PCT for the 59 calculations. Figures A-11 through A-21 show important parameters from the S-RELAP5 limiting calculation. Figure A-11 is the plot of PCT independent of elevation.

The analysis reported herein is for a rated core thermal power level of 4,590 MWt, a complete core of AREVA NP fuel, a steam generator tube plugging level of 5 percent in each generator, a total peaking factor (F_Q) of 2.60 and a nuclear enthalpy rise factor ($F_{\Delta H}$) of 1.70. The analysis supports peak rod average exposures of up to 62,000 MWd/mtU. The analysis considers no K_Z constraint on axial peaking; that is, K_Z is set equal to one for all core elevations. Also, no core peaking burnup constraints are applied.

The results of the RLBLOCA analysis show that the PCT for the limiting U.S. EPR case is 1,425 °F. Maximum oxidation thickness and hydrogen generation are well within regulatory requirements.

Specifically, it is concluded for this U.S. EPR RLBLOCA sample problem that:

1. The calculated PCT for the limiting PCT case is less than 2,200 °F.
2. The maximum calculated local clad oxidation is less than 17 percent.
3. The maximum amount of core-wide oxidation does not exceed 1 percent of the fuel cladding.

A.3.0 *SER Compliance*

The Conditions and Limitations imposed by the RLBLOCA EM SER are addressed in Table A-4. This U.S. EPR application complies with all SER Conditions and Limitations. Since a number of non-limiting PCT cases exhibited a blowdown quench (SER Item 7), a discussion and justification for this behavior follows.

Five of the 59 cases that were analyzed as part of the RLBLOCA sample problem exhibited a quench of the PCT node before the end of blowdown. All of these cases were split breaks having break areas at the low end of the spectrum of break sizes analyzed (>0.5 ft^2). PCT temperatures ranged from 864 °F to 1179 °F, well below the limiting PCT of 1425 °F. The limiting case (a double-ended guillotine break) did not exhibit a blowdown quench.

Mechanistically, the observed quench occurs because the small break area limits break flow. This reduces the rates at which pressure and flow decrease at the PCT location compared to the limiting case. The resulting combination of higher core flow and pressure cools the clad sufficiently to enable a return to nucleate boiling.

A factor contributing to the occurrence of blowdown quench in these U.S. EPR cases is the low peak power density of 13.56 kW/ft. In comparison, the analyses presented in the Reference A-1 sample problem, which did not exhibit blowdown quench, had a peak power density of 15.7 kW/ft. The lower peak power density results in less severe heatups and facilitates quenching. It also contributes to a lower maximum PCT of 1425 °F versus 1853 °F for the Reference A-1 analysis.

It is therefore concluded that the predicted blowdown quench behavior is appropriate for these non-limiting cases and that the RLBLOCA EM (Reference A-1) is applicable to the U.S. EPR without modification.

A.4.0 *References*

A-1. "Realistic Large Break LOCA Methodology for Pressurized Water Reactors," EMF-2103(P)(A) Revision 0, FANP Richland, Inc., April 2003.

A-2. "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," NUREG-0800, LWR edition, Revision 2, U.S. Nuclear Regulatory Commission, July 1987.

Table A-1 MHSI Flow Rates per Pump

Pressure Cold Leg[2] (psia)	Pressure SI Piping[3] (psia)	Flow Rate (lbm/s)
14.5	21.2	130.1
145.0	151.6	117.3
290.0	296.6	105.5
435.0	441.5	94.0
580.0	586.5	82.3
725.0	731.5	70.0
870.0	876.4	56.7
1015.0	1021.0	41.8
1160.0	1166.0	24.1
1233.0	1239.0	13.0
1305.0	-	-

Table A-2 LHSI Flow Rates per Pump

Pressure Cold Leg[2] (psia)	Pressure SI Piping[3] (psia)	Flow Rate (lbm/s)
14.5	36.4	312.2
58.0	76.8	273.2
87.0	104.0	248.4
116.0	131.4	223.4
145.0	159.0	197.6
174.0	186.6	170.7
203.0	214.4	141.9
232.0	242.4	110.5
261.0	270.5	75.1
290.0	298.9	32.3
311.0	-	-

[2] Not used to specify injection flow. Location is downstream of injection points.

[3] This is the local pressure within Safety Injection piping. Using Train 1 as typical or representative, this is the volume average pressure at volume 963-1 for LHSI and volume 965 for MHSI (see Figure A-6).

Table A-3 RLBLOCA Analysis Plant Parameter Values

	Parameter Description	Parameter Value
1.0	Plant Physical Description	
	1.1 Fuel	
	a) Cladding outside diameter	0.374 in
	b) Cladding inside diameter	0.329 in
	c) Cladding thickness	0.0225 in
	d) Pellet outside diameter	0.3225 in
	e) Pellet density	96% of theoretical
	f) Active fuel length	165.354 in
	g) Gd_2O_3 Concentration	2 – 8 w/o
	1.2 RCS	
	a) Flow resistance	Analysis
	b) Pressurizer location	Analysis assumes location giving most limiting PCT (broken loop)
	c) Hot assembly location	Anywhere in core
	d) Hot assembly type	17 x 17
	e) SG tube plugging	≤ 5%
2.0	Plant Initial Operating Conditions	
	2.1 Reactor Power	
	a) Core power	≤ 4,590 MWt (± 22 MWt (heat balance uncertainty))
	b) Maximum core peaking (FQ)	≤ 2.60[4] (normalized)
	c) Maximum pin radial peaking (FΔH)	≤ 1.70[5] (normalized)
	d) MTC	≤ 0 at HFP
	e) HFP natural boron equivalent	1,544 ppm (BOC)
	2.2 Fluid Conditions	
	a) Loop flow (total RCS flow)	176.44 Mlbm/hr ≤ M ≤ 198.00 Mlbm/hr
	b) RCS average temperature	589 °F ≤ T ≤ 599 °F
	c) Nominal upper head temperature	594 °F (average)
	d) Pressurizer pressure	2,214 psia ≤ P ≤ 2,286 psia
	e) Pressurizer level	49.3 % ≤ L ≤ 59.3 %
	f) Accumulator pressure	653 psia ≤ P ≤ 711 psia
	g) Accumulator (one of four) liquid volume	1,236 ft^3 ≤ V ≤ 1,413 ft^3
	h) Accumulator temperature	59 °F ≤ T ≤ 122 °F (coupled to containment temperature)
	i) Accumulator line resistance	Design piping configuration
	j) Minimum ECCS natural boron equivalent	≥ 2,563 ppm

4 Includes measurement and engineering uncertainties.
5 Was increased by 4% to account for measurement uncertainty.

Table A-3 RLBLOCA Analysis Plant Parameter Values (continued)

	Parameter Description	Parameter Value
3.0	Accident Boundary Conditions	
	a) Break location	Cold leg in loop containing the pressurizer
	b) Break type	Double-ended guillotine or split
	c) Break size per side (relative to cold leg pipe)	$0.05 \le A \le 0.5$ full pipe area (split) $0.5 \le A \le 1.0$ full pipe area (guillotine)
	d) Worst single failure	Loss of one complete train of MHSI and LHSI
	e) Offsite power	On or Off (sampled parameter)
	f) Medium-head safety injection flow	Minimum flow per pump w/o spillage (Table A-1)
	g) Low-head safety injection flow	Minimum flow per pump w/o spillage (Table A-2), flow splits calculated by S-RELAP5
	h) IRWST temperature	≤ 140 °F[6]
	i) Safety injection delay	≤ 15 seconds (with offsite power) ≤ 40 seconds (without offsite power)
	j) Containment pressure (initial)	14.7 psia
	k) Containment temperature	59 °F ≤ T ≤ 122 °F
	l) Containment sprays	N/A

[6] Including an allowance for drainage or spillage from the RCS pipe break.

Table A-4 SER Conditions and Limitations

SER Conditions and Limitations	Response
1. A CCFL violation warning will be added to alert the analyst to a CCFL violation in the downcomer should such occur.	There was no significant occurrence of CCFL violations in the downcomer for this analysis.
2. AREVA NP has agreed that it is not to use nodalization with hot leg to downcomer nozzle gaps.	Hot leg nozzle gaps were not modeled.
3. If AREVA NP applies the RLBLOCA methodology to plants using a higher planar linear heat generation rate (PLHGR) than used in the current analysis, or if the methodology is to be applied to an end-of-life analysis for which the pin pressure is significantly higher, then the need for a blowdown cladding rupture model will be reevaluated. The evaluation may be based on relevant engineering experience and should be documented in either the RLBLOCA guideline or plant specific calculation file.	The PLHGR for U.S. EPR is lower than the defined limit for the RLBLOCA EM (Reference A-1). An end-of-life calculation was not performed; thus, the need for a blowdown cladding rupture model was not reevaluated.
4. Slot breaks on the top of the pipe have not been evaluated. These breaks could cause the loop seals to refill during late reflood and the core to uncover again. These break locations are an oxidation concern as opposed to a PCT concern since the top of the core can remain uncovered for extended periods of time. Should an analysis be performed for a plant with loop seals with bottom elevations that are below the top elevation of the core, AREVA NP will evaluate the effect of the deep loop seal on the slot breaks. The evaluation may be based on relevant engineering experience and should be documented in either the RLBLOCA guideline or plant-specific calculation file.	This evaluation is performed in accordance with the method documented in the RLBLOCA guideline.
5. The model applies to 3- and 4-loop Westinghouse- and CE-designed nuclear steam systems.	The RLBLOCA EM is applicable to U.S. EPR, a 4-loop plant. This was discussed and justified in Section 4.0.
6. The model applies to bottom reflood plants only (cold side injection into the cold legs at the reactor coolant discharge piping).	The RLBLOCA EM is applicable to U.S. EPR since it is a bottom reflood plant.
7. The model is valid as long as blowdown quench does not occur. If blowdown quench occurs, additional justification for the blowdown heat transfer model and uncertainty are needed or the calculation is corrected. A blowdown quench is characterized by a temperature reduction of the peak cladding temperature (PCT) node to saturation temperature during the blowdown period.	The limiting PCT case showed no evidence of blowdown quench. Blowdown quenches were observed in a few (5) cases. An explanation of this behavior is provided in Section A.3.0.
8. The reflood model applies to bottom-up quench behavior. If a top-down quench occurs, the model is to be justified or corrected to remove top quench. A top-down quench is characterized by the quench front moving from the top to the bottom of the hot assembly.	Examination of the case set showed that core quench initiated at the bottom of the core and proceeded upward.
9. The model does not determine whether Criterion 5 of 10CFR50.46, long-term cooling, has been satisfied. This will be determined by each applicant or licensee as part of its application of this methodology.	Long-term cooling will be addressed in the Design Certification Application.

SER Conditions and Limitations	Response
10. Specific guidelines must be used to develop the plant-specific nodalization. Deviations from the reference plant must be addressed.	The model nodalization is consistent with the sample calculations given in the RLBLOCA EM (Reference A-1), except for changes incorporated to reflect current modeling guidelines and U.S. EPR-specific hardware. Significant changes are noted below. Accumulator Line: The accumulator line is shown in Figure A-1. For U.S. EPR, the accumulator line piping run between the check valve and the connection to the cold leg is quite long, about 25 feet. Hence, the normal single node (in the base EM) is divided into two nodes to minimize connecting nodes of disparate size. Steam Generator Axial Economizer: The SG is shown in Figure A-2. On the secondary side of the U.S. EPR U-tube SG, the bottom half of the downcomer and most of the tube region is physically divided into a hot and cold side. This coupled with the component size and the location of the separators and dryers require obvious noding changes (relative to the base EM) for proper representation. Nevertheless, all changes were implemented mindful of maintaining conformity with the base model concept. Inverted Top Hat: The RV upper head is shown in Figure A-3. The U.S. EPR UH is configured in what is commonly termed an “inverted top hat.” A section of the UH extends (below the top of the downcomer) into what is usually the top of the upper plenum. To properly model the UH, the region extending into what is usually the top of the UP is modeled as a separate node. Hence, the U.S. EPR UH consists of three nodes instead of the two nodes in the base EM. Heavy Reflector: The heavy reflector is also shown in Figure A-3. It consists of a set of massive plates surrounding the fuel assemblies. It replaces both the former and core baffle plates. The heavy reflector contains a series of flow holes, allowing fluid to both cool the reflector and bypass the core. The reflector is properly configured in the U.S. EPR model—both as a heat structure and a core flow bypass device.

SER Conditions and Limitations	Response
11. A table that contains the plant-specific parameters and the range of the values considered for the selected parameter during the topical report approval process must be provided. When plant-specific parameters are outside the range used in demonstrating acceptable code performance, the licensee or applicant will submit sensitivity studies to show the effects of that deviation.	Table A-9 presents the summary of the full range of applicability for the important heat transfer correlations, as well as the ranges calculated in the limiting analysis case. Calculated values for other parameters of interest are also provided. As is evident, the plant-specific parameters fall within the applicability range of the methodology. This is evidence of the applicability of the NRC-approved RLBLOCA EM to the U.S. EPR plant.
12. The licensee or applicant using the approved methodology must submit the results of the plant-specific analyses, including the calculated worst break size, PCT and local and total oxidation.	Analysis results are presented in Section A.2.0.
13. Applicants or licensees wishing to apply the AREVA NP realistic large break loss-of-coolant accident (RLBLOCA) methodology to M5® clad fuel must request an exemption for its use until the planned rulemaking to modify 10CFR50.46(a)(i) to include M5® cladding material has been completed.	AREVA NP understands that an exemption request is required for the use of M5® cladding. An exemption request is planned as part of Design Certification.

Table A-5 Statistical Distributions Used for Process Parameters

Parameter	Operational Uncertainty Distribution	Parameter Range
Core Power (%)	Uniform	99.52 – 100.48
Total Initial Flow Rate (Mlbm/hr)	Uniform	176.44 – 198.00
Initial Average Operating Temperature (°F)	Uniform	589 – 599
Pressurizer Pressure (psia)	Uniform	2,214 –2,286
Pressurizer Level (%)	Uniform	49.3 – 59.3
Containment Volume (x 10^6 ft^3)	Uniform	2.888 – 3.645[7]
Containment Temperature (°F)	Uniform	59 – 122
Accumulator Pressure (psia)	Uniform	652.7 – 710.7
Accumulator (one of four) Volume (ft^3)	Uniform	1,236 – 1,413
Intact Loop Number	Uniform	1, 2, and 4

Table A-6 Summary of Major Parameters for Limiting Transient

Time (hrs)	10,131
Burnup (MWd/mtU)	20,000
Core Power (MWt)	4,570
Core Peaking (F_Q)	2.578
Radial Peak ($F_{\Delta H}$)	1.70
Break Type	DEGB
Break Size per Side (ft^2)	3.3220 (~64.6%)
Offsite Power Availability	Yes
Decay Heat Multiplier	0.96132

[7] The lower bound is a nominal value, representing the combined volumes of gas and water; maximum value is gross volume of empty containment with nominal dimensions.

Table A-7 Summary of Results for the Limiting PCT Case

Case Number	44
Fuel Type (hot rod)	4% Gadolinia
PCT	
Temperature	1,425 °F
Time	33.9 s
Elevation	2.2 ft
Metal-Water Reaction	
% Oxidation Maximum	0.2354 %
% Total Oxidation	< 0.01 %

Table A-8 Calculated Event Times for the Limiting PCT Case

Event	Time (sec)
Begin analysis	0
Break opened	0
RCP tripped	10.3
SIAS issued	10.3
Start of broken loop accumulator injection (loop 3)	14.4
Start of intact loop accumulator injection	18.4
Start of MHSI	25.3
Broken loop MHSI delivery began (loop 3)	25.3
Intact loop MHSI delivery began (loop 4)	25.3
LHSI available	25.3
Broken loop LHSI delivery began (loop 3)	29.6
LHSI train 4 starts to deliver flow[8]	29.6
LHSI train 4 began delivery to (intact) loop 4[8]	46
Beginning of core recovery (beginning of reflood)	33.9
PCT occurred (1425 °F)	33.9
Broken loop accumulator emptied (loop 3)	64.9
Intact loop accumulator emptied (loop 1, 2, and 4 respectively)	62.4, 63.3, 65.5
Transient calculation terminated	200.0

[8] Between approximately 30 and 46 seconds, Train 4 of LHSI delivers to the broken loop through the cross connecting piping.

Table A-9 Heat Transfer Parameters for the Limiting Case[9]

[9] Values in brackets show full range of applicability as documented in Reference A-1.

Figure A-1 RLBLOCA Loop Noding Diagram

Figure A-2 Secondary Noding

Figure A-3 RLBLOCA RV Noding Diagram

Figure A-4 Core Noding Detail

Figure A-5 Upper Plenum Noding Detail

Figure A-6 Nodalization for S-RELAP5 ECCS Model

Figure A-7 Scatter Plot of Operational Parameters

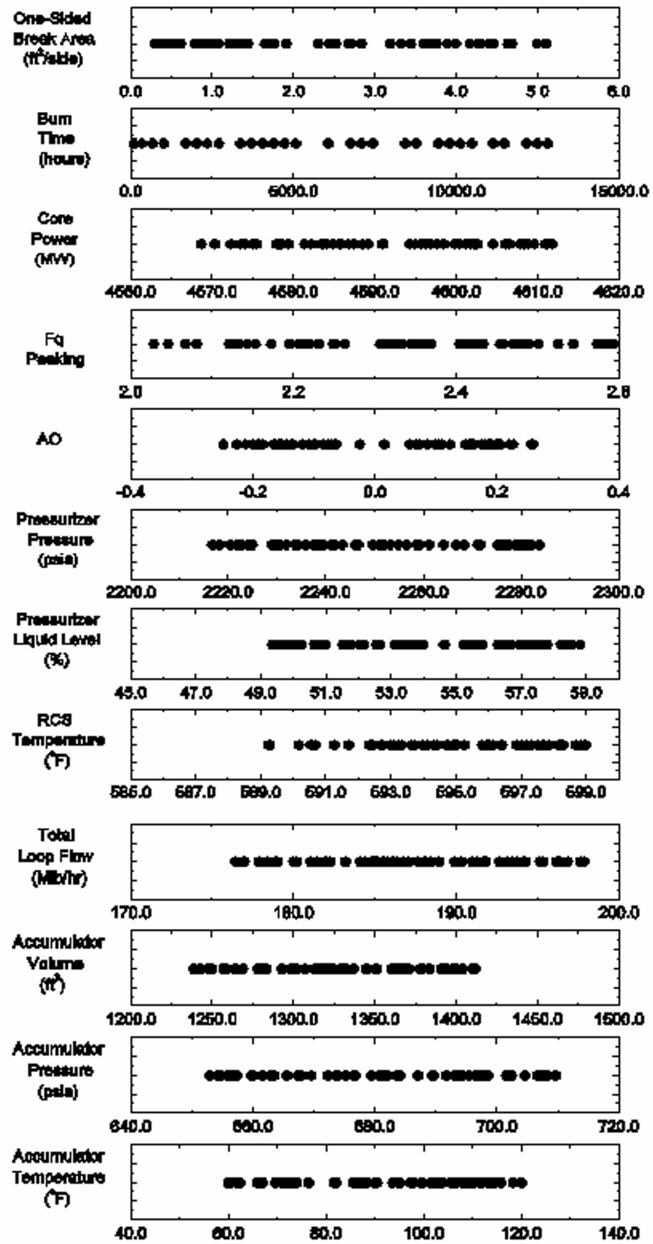


Figure A-8 PCT versus PCT Time Scatter Plot

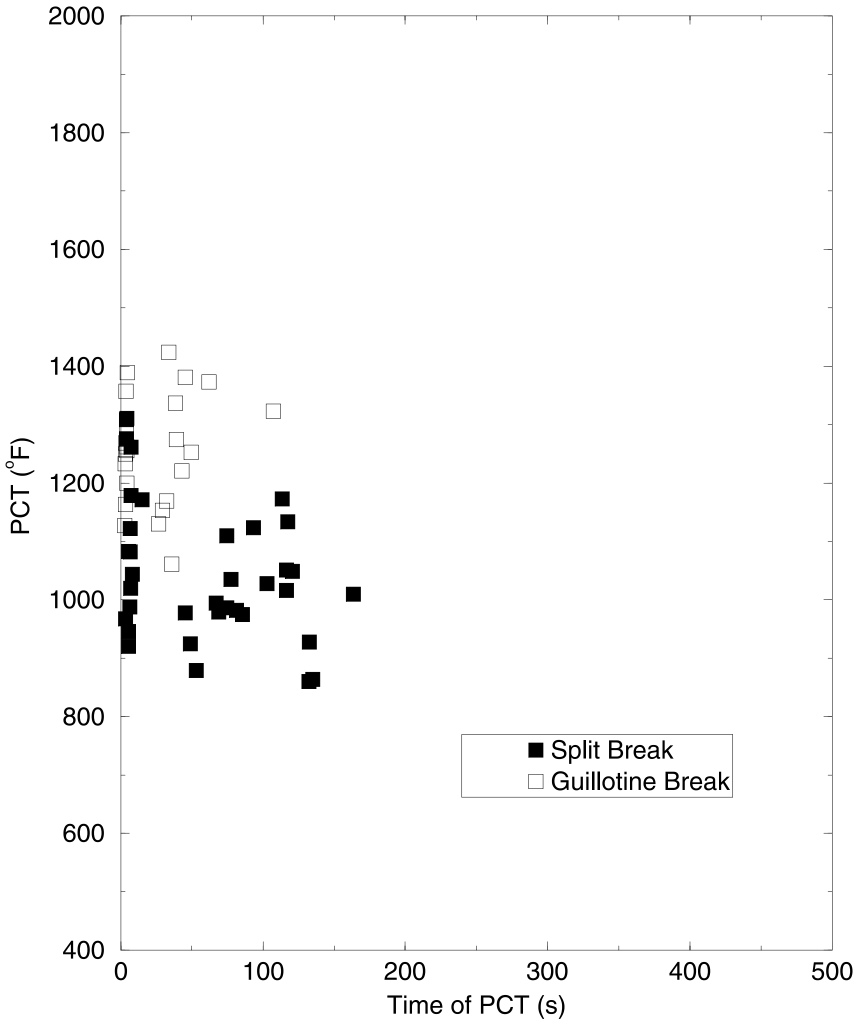


Figure A-9 PCT versus One-Sided Break Area Scatter Plot

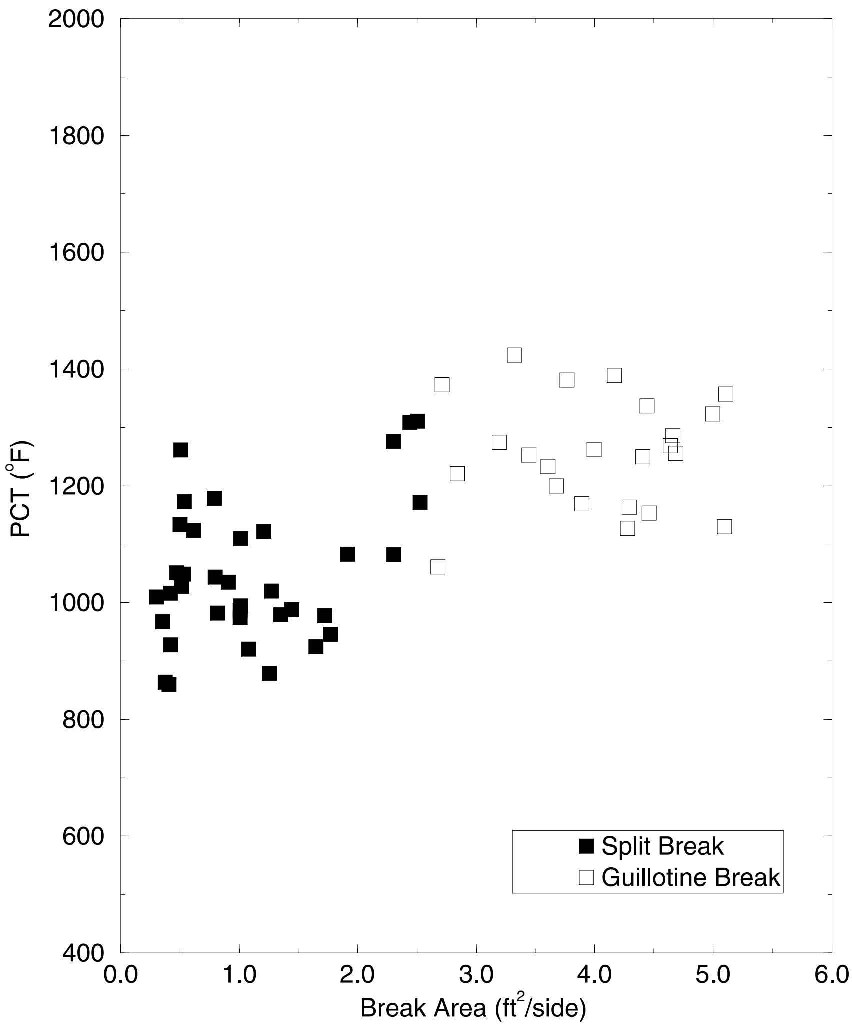


Figure A-10 Maximum Oxidation versus PCT Scatter Plot

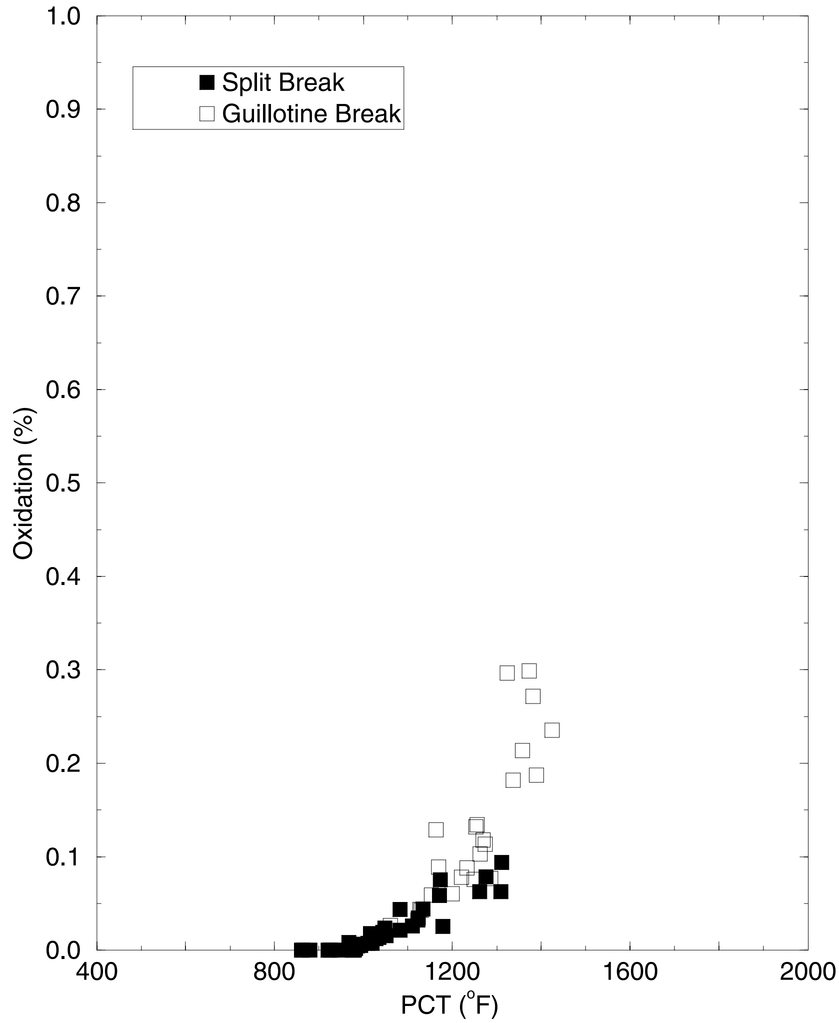


Figure A-11 Peak Cladding Temperature for the Limiting Break (elevation independent)

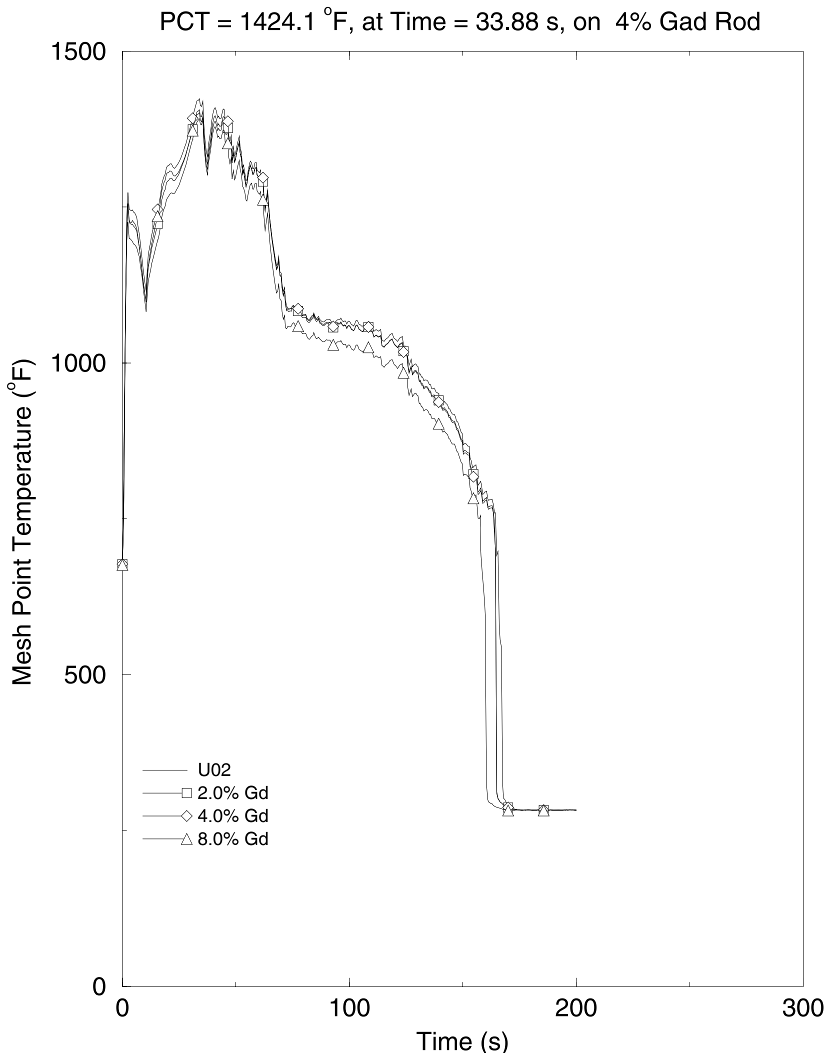


Figure A-12 Break Flow for the Limiting Break

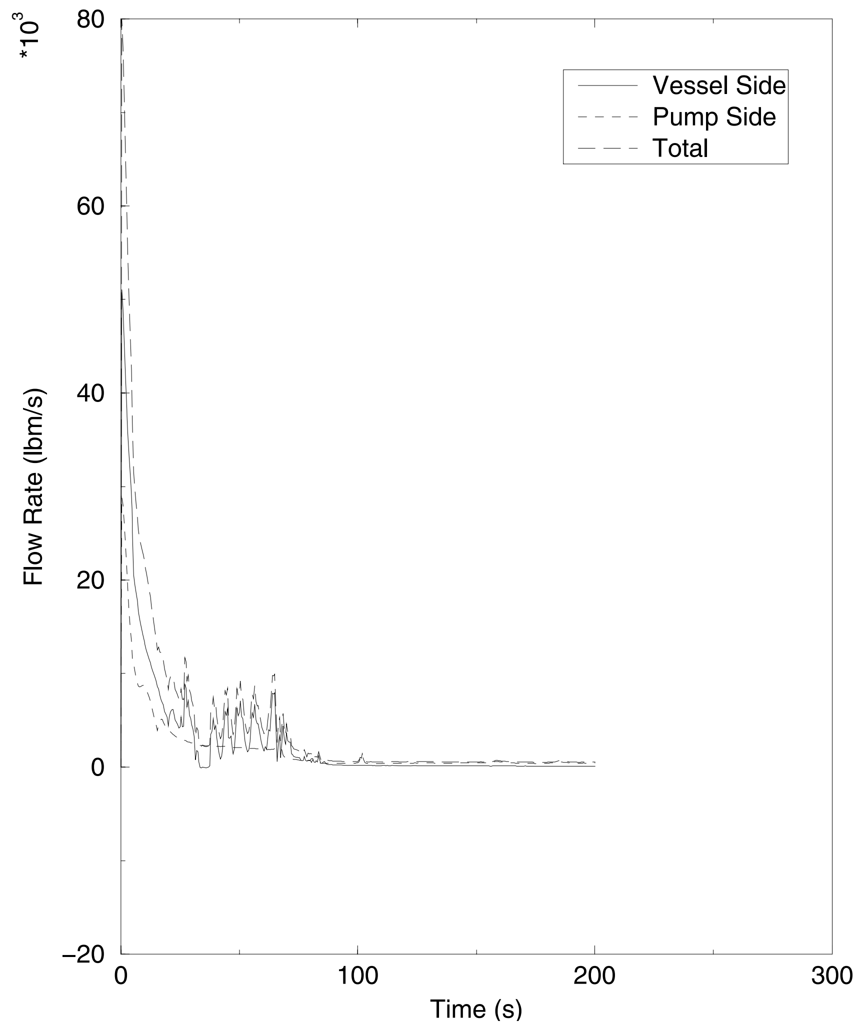


Figure A-13 Core Inlet Mass Flux for the Limiting Break

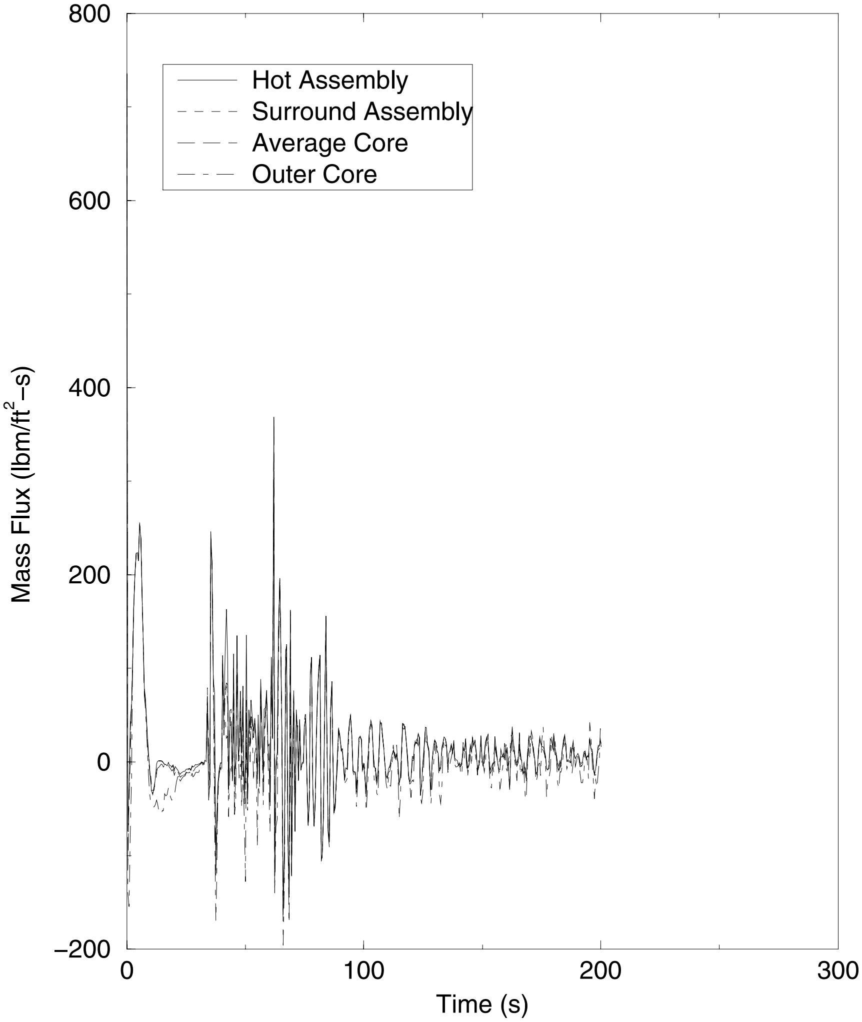


Figure A-14 Core Outlet Mass Flux for the Limiting Break

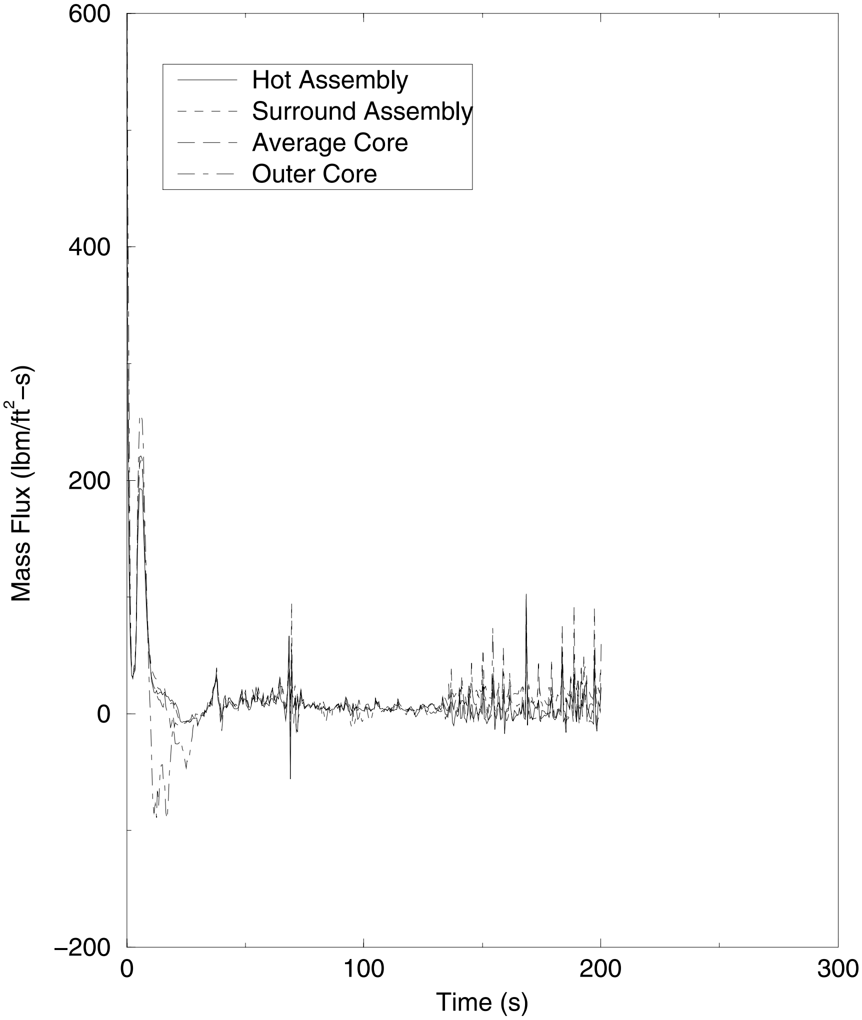


Figure A-15 Void Fraction at RCS Pumps for the Limiting Break

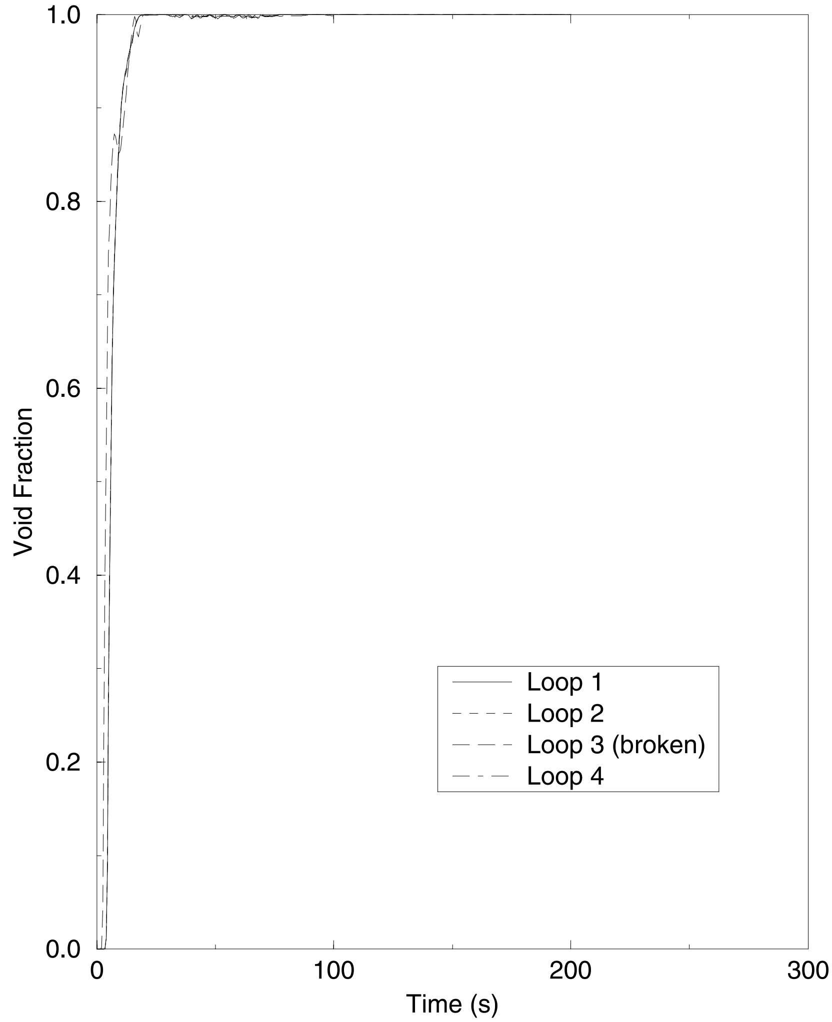


Figure A-16 ECCS Flows (includes Accumulator, MHSI and LHSI) for the Limiting Break

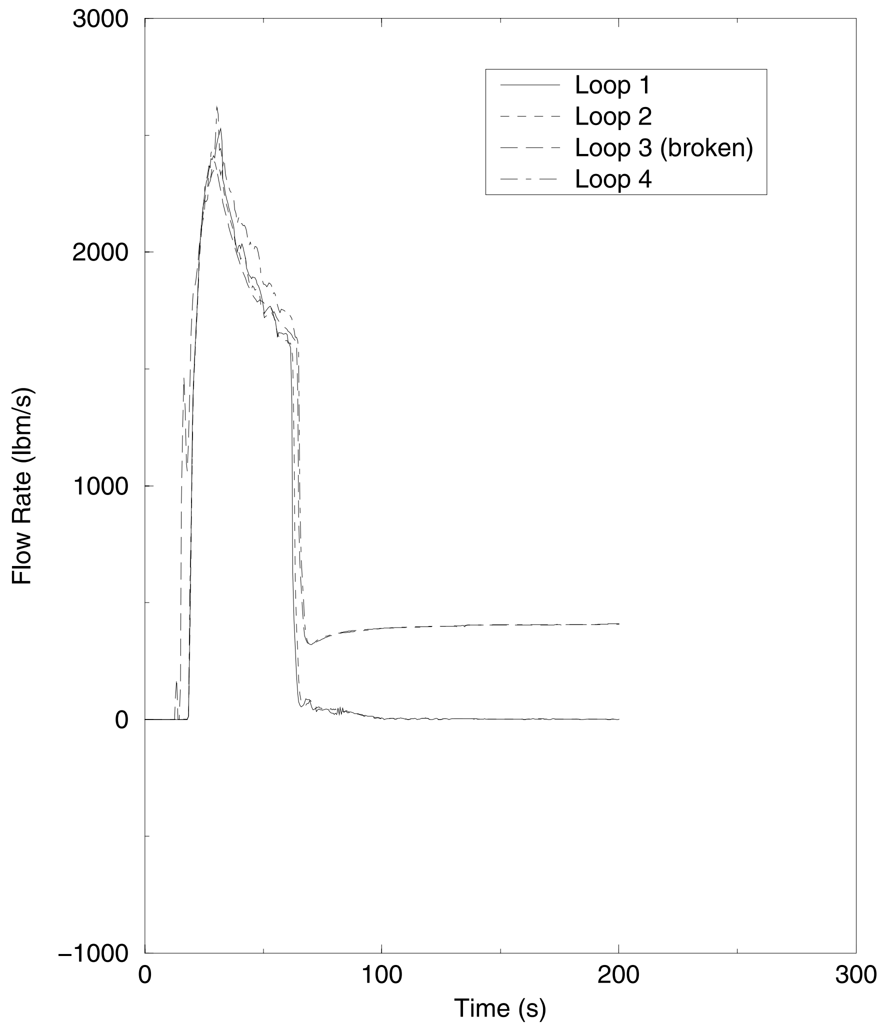


Figure A-17 System Pressure (Upper Plenum) for the Limiting Break

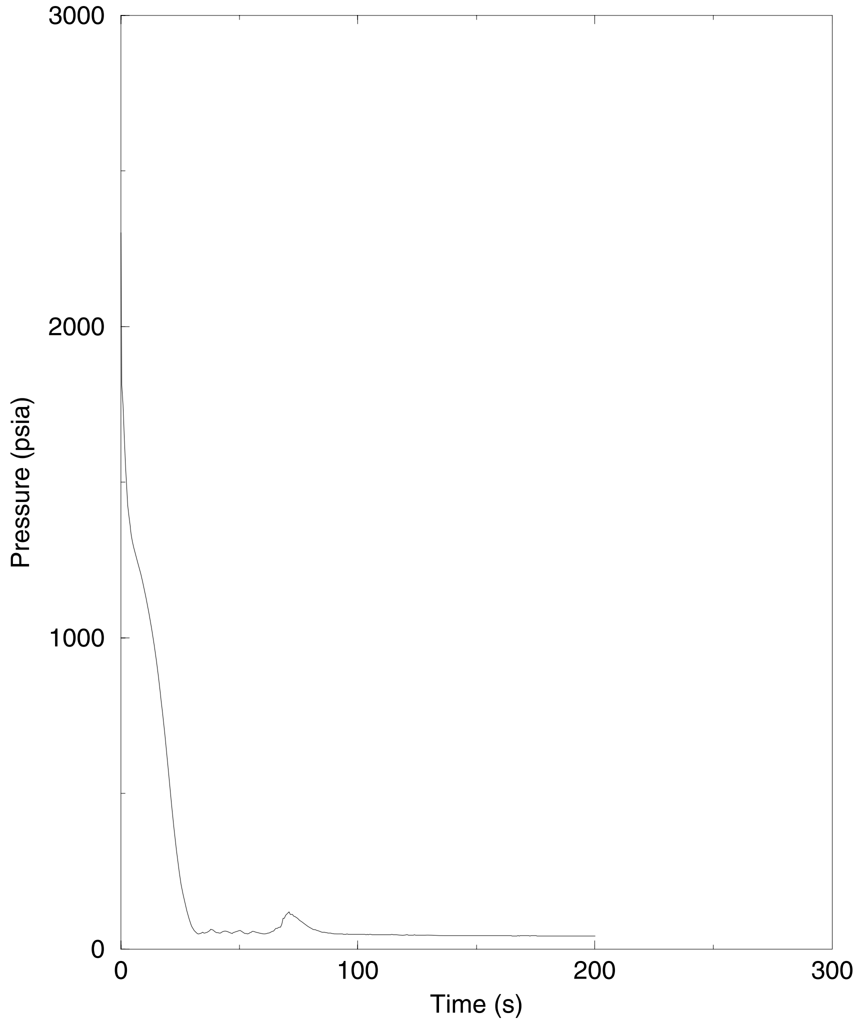


Figure A-18 Collapsed Liquid Level in the Downcomer for the Limiting Break

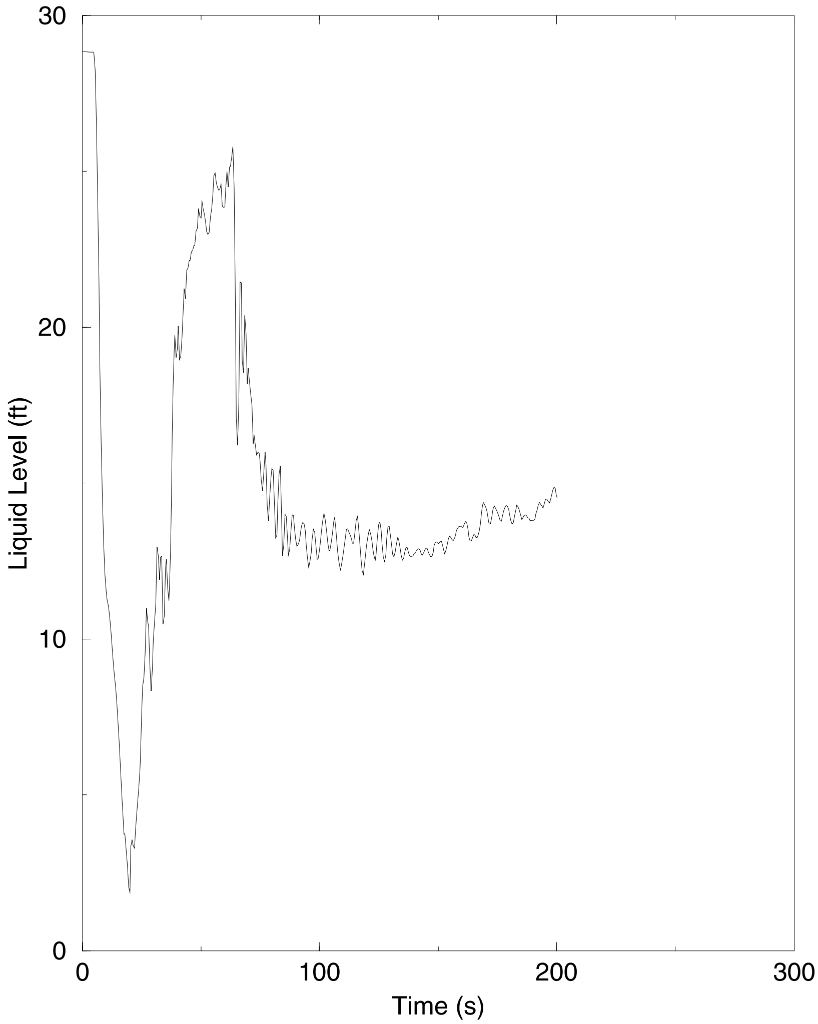


Figure A-19 Collapsed Liquid Level in the Lower Vessel for the Limiting Break

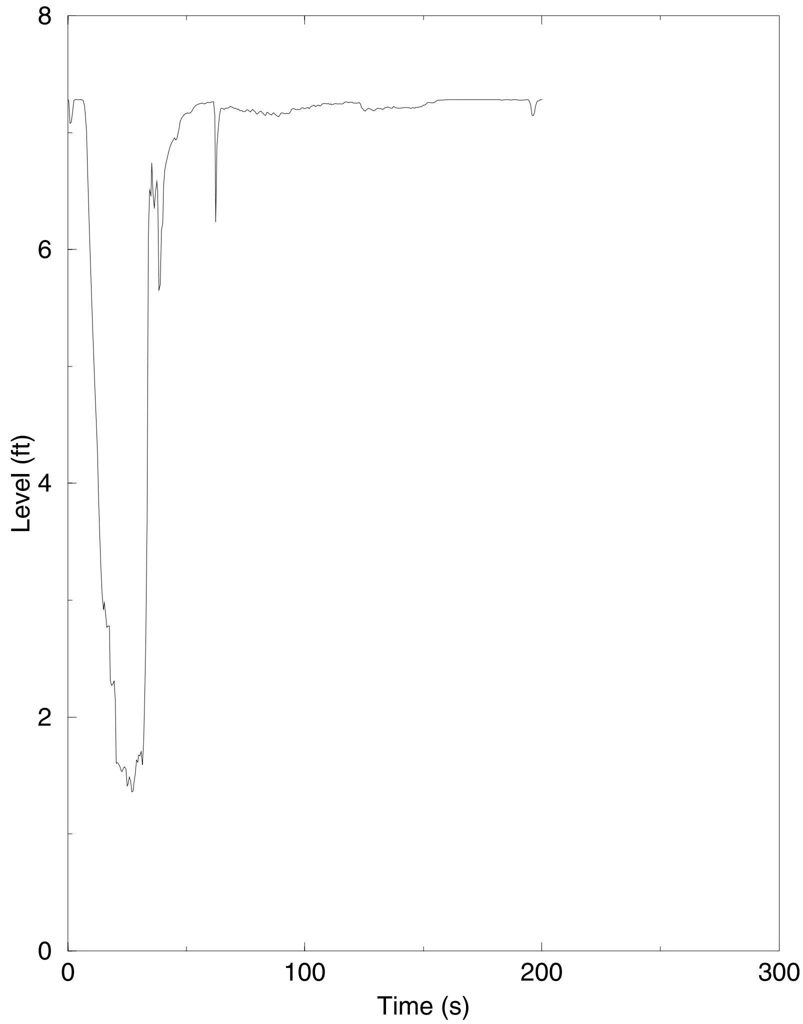


Figure A-20 Collapsed Liquid Level in the Core for the Limiting Break

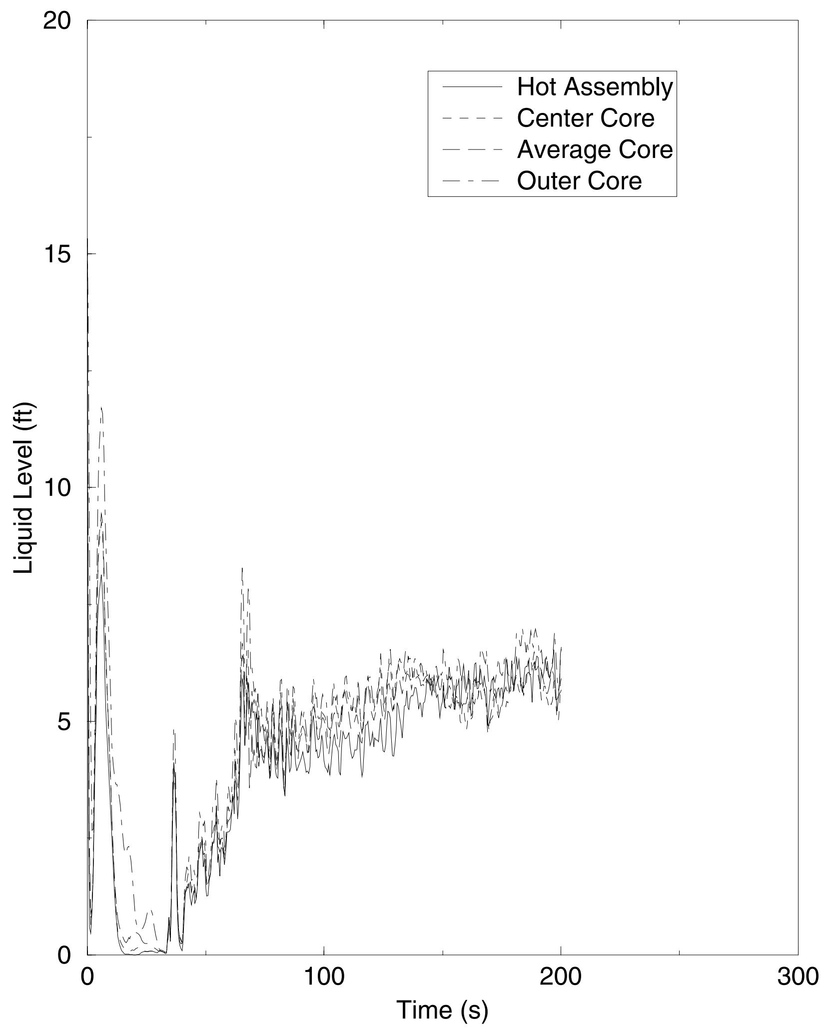


Figure A-21 Containment and Loop Pressures for the Limiting Break