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Enclosure 6

AREVA Report ANP-2625(NP), Revision 0,
Brunswick Units 1 and 2 LOCA Break Spectrum Analysis for ATRIUM™-10 Fuel,
dated June 2007

ANP-2625(NP)
Revision 0

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ATRIUM™-10 Fuel

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Nature of Changes

Item	Page	Description and Justification
1.	All	This is the initial issue.

Contents

Tables

Figures

Figures *(Continued)*

Figures *(Continued)*

Nomenclature

ADS	automatic depressurization system
ADSVOOS	ADS valve out of service
ANS	American Nuclear Society
BOL	beginning of life
BWR	boiling-water reactor
CFR	Code of Federal Regulations
CHF	critical heat flux
CMWR	core average metal-water reaction
DEG	double-ended guillotine
DG	diesel generator
ECCS	emergency core cooling system
EOB	end of blowdown
FHOOS	feedwater heaters out of service
HPCI	high-pressure coolant injection
LOCA	loss-of-coolant accident
LPCI	low-pressure coolant injection
LPCS	low-pressure core spray
MAPLHGR	maximum average planar linear heat generation rate
MCPR	minimum critical power ratio
MSIVOOS	main steam isolation valve out of service
MWR	metal-water reaction
NRC	Nuclear Regulatory Commission, U.S.
PCT	peak cladding temperature
RDIV	recirculation discharge isolation valve
SF-BATT	single failure of battery (DC) power
SF-HPCI	single failure of the HPCI system
SF-LPCI	single failure of an LPCI valve
SLO	single-loop operation
TLO	two-loop operation
UFSAR	updated final safety analysis report

1.0 Introduction

The results of a loss-of-coolant accident (LOCA) break spectrum analysis for Brunswick Units 1 and 2 are documented in this report. The purpose of the break spectrum analysis is to identify the parameters that result in the highest calculated peak cladding temperature (PCT) during a postulated LOCA. The LOCA parameters addressed in this report include the following:

- Break location
- Break type (double-ended guillotine (DEG) or split)
- Break size
- Limiting emergency core cooling system (ECCS) single failure
- Axial power shape (top- or mid-peaked)

The analyses documented in this report were performed with LOCA Evaluation Models developed by AREVA NP,* and approved for reactor licensing analyses by the U.S. Nuclear Regulatory Commission (NRC). The models and computer codes used by AREVA for LOCA analyses are collectively referred to as the EXEM BWR-2000 Evaluation Model (References 1 – 4). The EXEM BWR-2000 Evaluation Model and NRC approval are documented in Reference 1. A summary description of the LOCA analysis methodology is provided in Section 4.0. The calculations described in this report were performed in conformance with 10 CFR 50 Appendix K requirements and satisfy the event acceptance criteria identified in 10 CFR 50.46.

The break spectrum analyses documented in this report were performed for a core composed entirely of ATRIUM™-10† fuel at beginning-of-life (BOL) conditions. Calculations assumed an initial core power of 102% of 2923 MWt, providing a licensing basis power of 2981.46 MWt. The 2.0% increase reflects the maximum uncertainty in monitoring reactor power, as per NRC requirements. The limiting assembly in the core was assumed to be at a maximum average planar linear heat generation rate (MAPLHGR) limit of 12.5 kW/ft. The analyses assumed a generic ATRIUM-10 neutronic design that is expected to be conservative relative to actual cycle-specific designs. Other initial conditions used in the analyses are described in Section 4.0.

This report identifies the limiting LOCA break characteristics (location, type, size, single failure and axial power shape) that will be used in future analyses to determine the MAPLHGR limit

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* AREVA NP Inc. is an AREVA and Siemens company.

† ATRIUM is a trademark of AREVA NP.

versus exposure for ATRIUM-10 fuel contained in Brunswick Units 1 and 2. Even though the limiting break will not change with exposure or nuclear fuel design, the value of PCT calculated for any given set of break characteristics is dependent on exposure and local power peaking. Therefore, heatup analyses are performed to determine the PCT versus exposure for each nuclear design in the core. The heatup analyses are performed each cycle using the limiting boundary conditions determined in the break spectrum analysis. The maximum PCT versus exposure from the heatup analyses are documented in the MAPLHGR report.

All analyses performed support operation with one automatic depressurization system (ADS) valve out of service (ADSVOOS). The analyses support recirculation loop flow mismatch operation of up to 5% of rated core flow. This report also presents results for single-loop operation (SLO) and long-term coolability.

2.0 Summary of Results

Based on analyses presented in this report, the limiting break characteristics are identified below.

Limiting LOCA Break Characteristics	
Location	Recirculation discharge pipe
Type / size	Double-ended guillotine / 0.8 discharge coefficient
Single failure	Low-pressure coolant injection valve
Axial power shape	Top-peaked

The LOCA break spectrum analysis results presented in this report are for Brunswick Unit 2 which conservatively bound the Unit 1 analysis. Analysis results show that the limiting PCT for Unit 1 is bound by the limiting PCT for Unit 2. A more detailed discussion of results is provided in Sections 6.0 – 7.0.

[

] The break characteristics identified in this report can be used in subsequent fuel type specific LOCA heatup analyses to determine the MAPLHGR limit appropriate for the fuel type.

The SLO LOCA analyses support operation with an ATRIUM-10 MAPLHGR multiplier of 0.85 applied to the normal two-loop operation MAPLHGR limit.

The long-term coolability evaluation confirms that the ECCS capacity is sufficient to maintain adequate cooling in an ATRIUM-10 core for an extended period after a LOCA.

All analyses support operation with one ADSVOOS. All analyses also support a 5% mismatch in the recirculation loop flows at the start of the LOCA. All analyses were performed assuming nominal feedwater temperature. [

] Therefore, this LOCA analysis supports FHOOS operation.

At Brunswick, operation with 1 MSIVOOS is limited to two-loop operation and power levels less than 70% of rated. For a given power level, 1 MSIVOOS can result in a higher reactor pressure at the initiation of a LOCA and a slightly higher break flow. [

] Therefore, this LOCA analysis supports operation with 1 MSIVOOS.

While the fuel rod temperatures in the limiting plane of the hot channel during a LOCA are dependent on exposure, the factors that determine the limiting break characteristics are primarily associated with the reactor system and are not dependent on fuel-exposure characteristics. Fuel parameters that are dependent on exposure (e.g., stored energy, local peaking) have an insignificant effect on the reactor system response during a LOCA. The limiting break characteristics determined using BOL fuel conditions are applicable for exposed fuel. Fuel exposure effects are addressed in heatup analyses performed to determine or verify MAPLHGR limits versus exposure for each fuel design.

3.0 LOCA Description

3.1 *Accident Description*

The LOCA is described in the Code of Federal Regulations 10 CFR 50.46 as a hypothetical accident that results in a loss of reactor coolant from breaks in reactor coolant pressure boundary piping up to and including a break equivalent in size to a double-ended rupture of the largest pipe in the reactor coolant system. There is not a specifically identified cause that results in the pipe break. However, for the purpose of identifying a design basis accident, the pipe break is postulated to occur inside the primary containment before the first isolation valve.

For a boiling water reactor (BWR), a LOCA may occur over a wide spectrum of break locations and sizes. Responses to the break vary significantly over the break spectrum. The largest possible break is a double-ended rupture of a recirculation pipe; however, this is not necessarily the most severe challenge to the emergency core cooling system (ECCS). A double-ended rupture of a main steam line causes the most rapid primary system depressurization, but because of other phenomena, steam line breaks are seldom limiting with respect to the event acceptance criteria (10 CFR 50.46). Because of these complexities, an analysis covering the full range of break sizes and locations is performed to identify the limiting break characteristics.

Regardless of the initiating break characteristics, the event response is conveniently separated into three phases: the blowdown phase, the refill phase, and the reflood phase. The relative duration of each phase is strongly dependent upon the break size and location. The last two phases are often combined and will be discussed together in this report.

During the blowdown phase of a LOCA, there is a net loss of coolant inventory, an increase in fuel cladding temperature due to core flow degradation, and for the larger breaks, the core becomes fully or partially uncovered. There is a rapid decrease in pressure during the blowdown phase. During the early phase of the depressurization, the exiting coolant provides core cooling. Low-pressure core spray (LPCS) also provides some heat removal. The end of the blowdown (EOB) phase is defined to occur when the system reaches the pressure corresponding to the rated LPCS flow.

In the refill phase of a LOCA, the ECCS is functioning and there is a net increase of coolant inventory. During this phase the core sprays provide core cooling and, along with low-pressure and high-pressure coolant injection (LPCI and HPCI), supply liquid to refill the lower portion of the reactor vessel. In general, the core heat transfer to the coolant is less than the fuel decay heat rate and the fuel cladding temperature continues to increase during the refill phase.

In the reflood phase, the coolant inventory has increased to the point where the mixture level reenters the core region. During the core reflood phase, cooling is provided above the mixture level by entrained reflood liquid and below the mixture level by pool boiling. Sufficient coolant eventually reaches the core hot node and the fuel cladding temperature decreases.

3.2 *Acceptance Criteria*

A LOCA is a potentially limiting event that may place constraints on fuel design, local power peaking, and in some cases, acceptable core power level. During a LOCA, the normal transfer of heat from the fuel to the coolant is disrupted. As the liquid inventory in the reactor decreases, the decay heat and stored energy of the fuel cause a heatup of the undercooled fuel assembly. In order to limit the amount of heat that can contribute to the heatup of the fuel assembly during a LOCA, an operating limit on the MAPLHGR is applied to each fuel assembly in the core.

The Code of Federal Regulations prescribes specific acceptance criteria (10 CFR 50.46) for a LOCA event as well as specific requirements and acceptable features for Evaluation Models (10 CFR 50 Appendix K). The conformance of the EXEM BWR-2000 LOCA Evaluation Models to Appendix K is described in Reference 1. The ECCS must be designed such that the plant response to a LOCA meets the following acceptance criteria specified in 10 CFR 50.46:

- The calculated maximum fuel element cladding temperature shall not exceed 2200°F.
- The calculated local oxidation of the cladding shall nowhere exceed 0.17 times the local cladding thickness.
- 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, except the cladding surrounding the plenum volume, 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.

These criteria are commonly referred to as the peak cladding temperature (PCT) criterion, the local oxidation criterion, the hydrogen generation criterion, the coolable geometry criterion, and the long-term cooling criterion. A MAPLHGR limit is established for each fuel type to ensure that these criteria are met. LOCA PCT results are provided in Sections 6.0 – 7.0 to determine the limiting LOCA event. LOCA analysis results demonstrating that the PCT, local oxidation, and hydrogen generation criteria are met are provided in follow-on MAPLHGR report and cycle specific heatup analyses performed to determine MAPLHGR limits versus exposure for each fuel design. Compliance with these three criteria ensures that a coolable geometry is maintained. Long-term coolability criterion is discussed in Section 8.0.

4.0 LOCA Analysis Description

The Evaluation Model used for the break spectrum analysis is the EXEM BWR-2000 LOCA analysis methodology described in Reference 1. The EXEM BWR-2000 methodology employs three major computer codes to evaluate the system and fuel response during all phases of a LOCA. These are the RELAX, HUXY, and RODEX2 computer codes. RELAX is used to calculate the system and hot channel response during the blowdown, refill and reflood phases of the LOCA. The HUXY code is used to perform heatup calculations for the entire LOCA, and calculates the PCT and local clad oxidation at the axial plane of interest. RODEX2 is used to determine fuel parameters (such as stored energy) for input to the other LOCA codes. The code interfaces for the LOCA methodology are illustrated in Figure 4.1.

A complete analysis for a given break size starts with the specification of fuel parameters using RODEX2 (Reference 4). RODEX2 is used to determine the initial stored energy for both the blowdown analysis (RELAX hot channel) and the heatup analysis (HUXY). This is accomplished by ensuring that the initial stored energy in RELAX and HUXY is the same or higher than that calculated by RODEX2 for the power, exposure, and fuel design being considered.

4.1 *Blowdown Analysis*

The RELAX code (Reference 1) is used to calculate the system thermal-hydraulic response during the blowdown phase of the LOCA. For the system blowdown analysis, the core is represented by an average core channel. The reactor core is modeled with heat generation rates determined from reactor kinetics equations with reactivity feedback and decay heat as required by Appendix K of 10 CFR 50. The reactor vessel nodalization for the system analysis is shown in Figure 4.2. This nodalization is consistent with that used in the topical report submitted to the NRC (Reference 1).

The RELAX blowdown analysis is performed from the time of the break initiation through the end of blowdown (EOB). The system blowdown calculation provides the upper and lower plenum transient boundary conditions for the hot channel analysis.

Following the system blowdown calculation, another RELAX analysis is performed to analyze the maximum power assembly (hot channel) of the core. The RELAX hot channel blowdown calculation determines hot channel fuel, cladding, and coolant temperatures during the blowdown phase of the LOCA. The RELAX hot channel nodalization is shown in Figure 4.3 for a top-peaked power shape, and in Figure 4.4 for a mid-peaked axial power shape. The hot channel analysis is performed using the system blowdown results to supply the core power and the system boundary conditions at the core inlet and exit. The initial average fuel rod temperature at the limiting plane of the hot channel is conservative relative to the average fuel rod temperature calculated by RODEX2 for operation of the ATRIUM-10 assembly at the MAPLHGR limit. The heat transfer coefficients and fluid conditions in the hot channel from the RELAX hot channel calculation are used as input to the HUXY heatup analysis.

4.2 *Refill/Reflood Analysis*

The RELAX code is also used to compute the system and hot channel hydraulic response during the refill/reflood phase of the LOCA. The RELAX system and RELAX hot channel analyses continue beyond the end of blowdown to analyze system and hot channel responses during the refill and reflood phases. The refill phase is the period when the lower plenum is filling due to ECCS injection. The reflood phase is the period when some portions of the core and hot assembly are being cooled with ECCS water entering from the lower plenum. The purpose of the RELAX calculations beyond blowdown is to determine the time when the liquid flow via upward entrainment from the bottom of the core becomes high enough at the hot node in the hot assembly to end the temperature increase of the fuel rod cladding. This event time is called the time of hot node reflood. [

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The RELAX calculations provide HUXY with the time of hot node reflood and the time when the liquid has risen in the bypass to the height of the axial plane of interest (time of bypass reflood).

4.3 *Heatup Analysis*

The HUXY code (Reference 2) is used to perform heatup calculations for the entire LOCA transient and provides PCT and local clad oxidation at the axial plane of interest. The heat generated by metal-water reaction (MWR) is included in the HUXY analysis. HUXY is used to calculate the thermal response of each fuel rod in one axial plane of the hot channel assembly. These calculations consider thermal-mechanical interactions within the fuel rod. The clad swelling and rupture models from NUREG-0630 have been incorporated into HUXY

(Reference 3). The HUXY code complies with the 10 CFR 50 Appendix K criteria for LOCA Evaluation Models.

HUXY uses the EOB time and the times of core bypass reflood and core reflood at the axial plane of interest from the RELAX analysis. [

] Throughout the calculations, decay power is determined based on the ANS 1971 decay heat curve plus 20% as described in Reference 1. [

] are used in the HUXY analysis. The principal results of a HUXY heatup analysis are the PCT and the percent local oxidation of the fuel cladding, often called the %MWR.

4.4 *Plant Parameters*

The LOCA break spectrum analysis is performed using the plant parameters provided by the utility. Table 4.1 provides a summary of reactor initial conditions used in the break spectrum analysis. Table 4.2 lists selected reactor system parameters.

The break spectrum analysis is performed for a full core of ATRIUM-10 fuel. Some of the key fuel parameters used in the break spectrum analysis are summarized in Table 4.3.

4.5 *ECCS Parameters*

The ECCS configuration is shown in Figure 4.5. Table 4.4 – Table 4.7 provide the important ECCS characteristics assumed in the analysis. The ECCS is modeled as fill junctions connected to the appropriate reactor locations: LPCS injects into the upper plenum, HPCI injects into the upper downcomer and LPCI injects into the recirculation lines. Although HCPI is expected to be available, no analysis mitigation credit is assumed for the HPCI system in any of the analyses discussed in this report.

The flow through each ECCS valve is determined based on system pressure and valve position. Flow versus pressure for a fully open valve is obtained by linearly interpolating the pump capacity data provided in Table 4.4 – Table 4.6. No credit for ECCS flow is assumed until the

ECCS injection valves are fully open. Also, no credit for ECCS flow is assumed until ECCS pumps reach rated speed.

The ADS valves are modeled as a junction connecting the reactor steam line to the suppression pool. The flow through the ADS valves is calculated based on pressure and valve flow characteristics. The valve flow characteristics are determined such that the calculated flow is equal to the rated capacity at the reference pressure shown in Table 4.7. Only five ADS valves are assumed operable in the analyses to support operation with one ADSVOOS and the potential single failure of one ADS valve during the LOCA.

In the AREVA LOCA analysis model, ECCS initiation is assumed to occur when the water level drops to the applicable level set point. No credit is assumed for the start of LPCS or LPCI due to high drywell pressure. [

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Table 4.1 Initial Conditions

Reactor power (% of rated)	102	102
[ ]		
Reactor power (MWt)	2981.5	2981.5
[ ]		
[ ]		
Steam flow rate (Mlb/hr)	13.1	13.1
Steam dome pressure (psia)	1048.8	1048.6
Core inlet enthalpy (Btu/lb)	527.7	522.4
ATRIUM-10 hot assembly MAPLHGR (kW/ft)	12.5	12.5
[ ]		
Axial power shapes	Figure 4.6	Figure 4.7

* [ ]

Table 4.2 Reactor System Parameters

Parameter	Value
Vessel ID (in)	220.5
Number of fuel assemblies	560
Recirculation suction pipe area (ft^2)	3.67
1.0 DEG suction break area (ft^2)	7.33
Recirculation discharge pipe area (ft^2)	3.67
1.0 DEG discharge break area (ft^2)	7.33

Table 4.3 ATRIUM-10 Fuel Assembly Parameters

Parameter	Value
Fuel rod array	10x10
Number of fuel rods per assembly	83 (full-length rods) 8 (part-length rods)
Non-fuel rod type	Water channel replaces 9 fuel rods
Fuel rod OD (in)	0.3957
Active fuel length (in) (including blankets)	149.45 (full-length rods) 90.0 (part-length rods)
Water channel outside width (in)	1.378
Fuel channel thickness (in)	0. 075 (minimum wall) 0. 100 (corner)
Fuel channel internal width (in)	5.278

Table 4.4 High-Pressure Coolant Injection Parameters

Parameter	Value
Coolant temperature (maximum) (°F)	140
Initiating Signals and Setpoints	
Water level (in)*	459
High drywell pressure (psig)	Not used
Time Delays	
Time for HPCI pump to reach rated speed and injection valve wide open (sec)	60
Delivered Coolant Flow Rate Versus Pressure	
Vessel to Torus ΔP (psid)	Flow Rate (gpm)
0	0
150	3825
1164	3825

* Relative to vessel zero.

Table 4.5 Low-Pressure Coolant Injection Parameters

Parameter		Value
Reactor pressure permissive for opening valves - analytical (psia)		410
Coolant temperature (maximum) (°F)		160
Initiating Signals and Setpoints		
Water level (in)*		358
High drywell pressure (psig)		Not used
Time Delays		
Time for LPCI pumps to reach rated speed (maximum) (sec)		31.8
LPCI injection valve stroke time (sec)		37.5
Delivered Coolant Flow Rate Versus Pressure		
Vessel to Torus ΔP (psid)	Flow rate for 1 pump injecting into 1 recirculation loop (gpm)	Flow rate for 2 pumps injecting into 1 recirculation loop (gpm)
0	8690	14,420
20	7000	12,000
202	0	0

* Relative to vessel zero.

Table 4.6 Low-Pressure Core Spray Parameters

Parameter	Value
Reactor pressure permissive for opening valves - analytical (psia)	410
Coolant temperature (maximum) (°F)	160
Initiating Signals and Setpoints	
Water level (in)*	358
High drywell pressure (psig)	Not used
Time Delays	
Time for LPCS pumps to reach rated speed (maximum) (sec)	39.7
LPCS injection valve stroke time (sec)	14.0
Delivered Coolant Flow Rate Versus Pressure	
Vessel to Torus ΔP (psid)	Flow rate for 1 pump (gpm)
0	5250
113	4000
265	0

* Relative to vessel zero.

Table 4.7 Automatic Depressurization System Parameters

Parameter	Value
Number of valves installed	7
Number of valves available*	5
Minimum flow capacity of available valves (Mlbm/hr at psig)	4.15 at 1112.4
Initiating Signals and Setpoints	
Water level (in)†	358
High drywell pressure (psig)‡	2
Time Delays	
ADS timer (delay time from initiating signal to time valves are open (sec)	121

* Only 5 valves are assumed operable in the analyses to support 1 ADSVOOS operation and the potential single failure of 1 ADS valve during the LOCA.

† Relative to vessel zero.

‡ [ ]

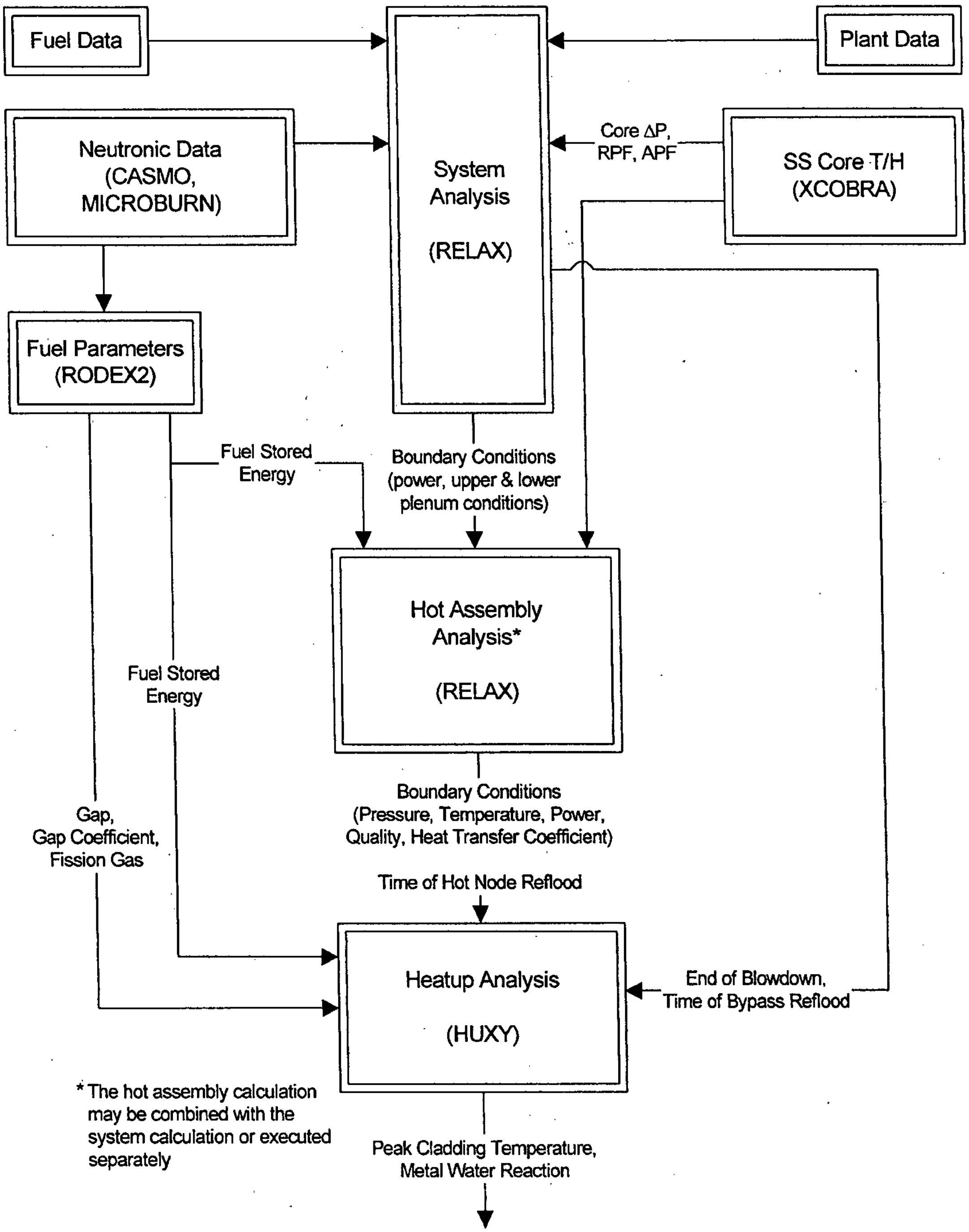

Figure 4.1 Flow Diagram for EXEM BWR-2000 ECCS Evaluation Model

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**Figure 4.2 RELAX System Model
(Recirculation Suction Break)**

[

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Figure 4.3 RELAX Hot Channel Model
Top-Peaked Axial

[

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**Figure 4.4 RELAX Hot Channel Model
Mid-Peaked Axial**

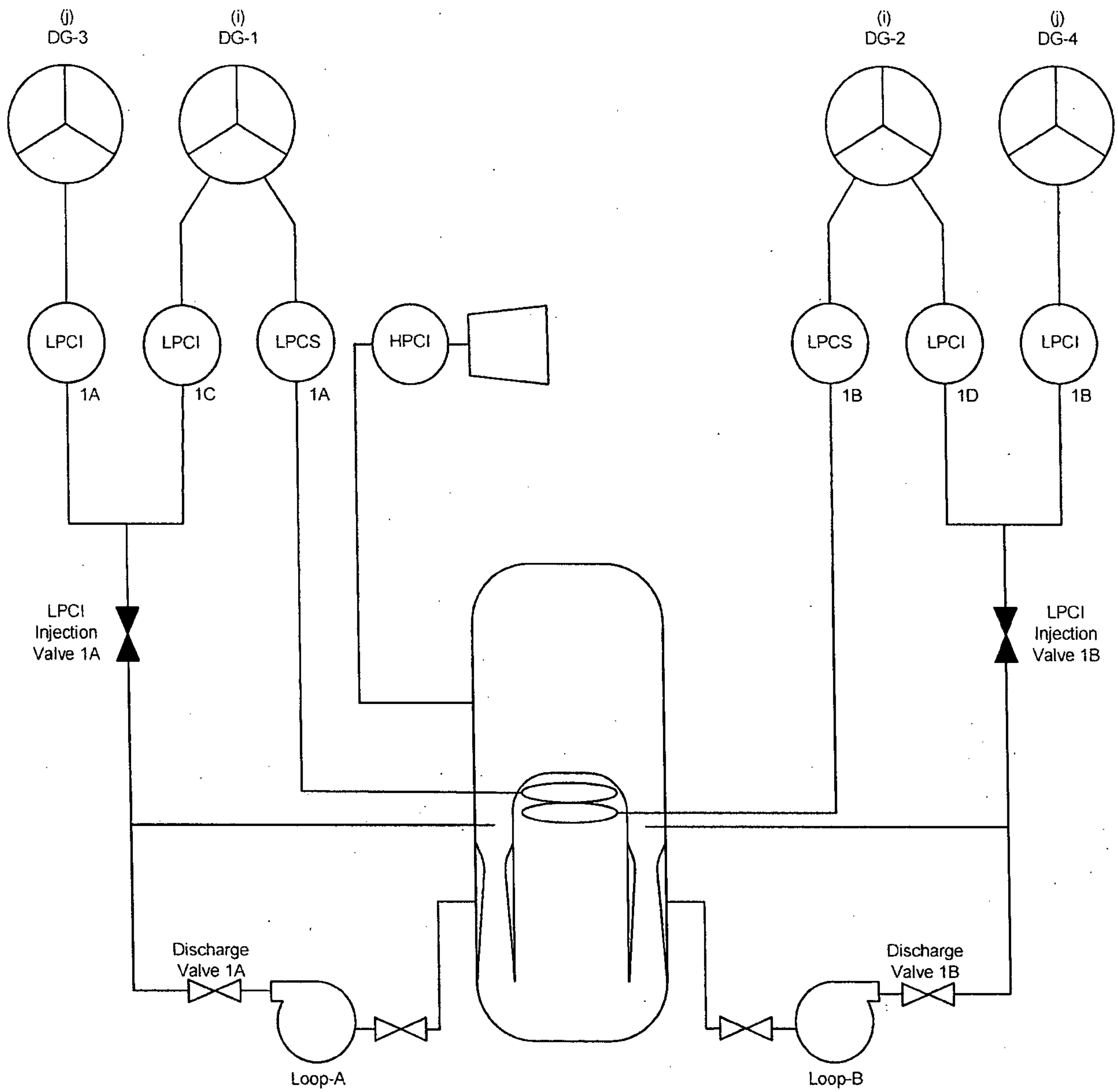

Figure 4.5 ECCS Schematic

[

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Figure 4.6 Axial Power Distributions for 102%P and [ ] Mid- and Top-Peaked

[

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Figure 4.7 Axial Power Distributions for 102%P and [ ] Mid- and Top-Peaked

5.0 Break Spectrum Analysis Description

The objective of this LOCA analyses is to ensure that the limiting break location, break type, break size, and ECCS single failure are identified. The LOCA response scenario varies considerably over the spectrum of break locations. Potential break locations have been separated into two groups: recirculation line breaks and non-recirculation line breaks. The basis for the break locations and potentially limiting single failures analyzed in this report is described in the following sections.

5.1 *Limiting Single Failure*

Regulatory requirements specify that the LOCA analysis be performed assuming that all offsite power supplies are lost instantaneously and that only safety grade systems and components are available. In addition, regulatory requirements also specify that the most limiting single failure of ECCS equipment must be assumed in the LOCA analysis. The term "most limiting" refers to the ECCS equipment failure that produces the greatest challenge to event acceptance criteria. The limiting single failure can be a common power supply, an injection valve, a system pump, or system initiation logic. The most limiting single failure may vary with break size and location. The potential limiting single failures identified in the UFSAR (Reference 6) are shown below:

- DC power (i) (SF-BATT)
- DC power (j)
- Diesel generator (i)
- Diesel generator (j)
- LPCI injection valve (SF-LPCI)
- High-pressure coolant injection system (SF-HPCI)

The single failures and the available ECCS for each failure assumed in these analyses are summarized in Table 5.1. Other potential failures are not specifically considered because they result in as much or more ECCS capacity.

As indicated earlier, no analysis mitigation credit is assumed for the HPCI system in any of the LOCA analyses presented in this report. A review of Table 5.1 shows that the DC power (i) and LPCI injection valve failures are the two potential limiting failures as the other single failures result in as much or more ECCS capacity. Only five ADS valves are assumed operable in the analyses to support operation with one ADSVOOS and the potential single failure of one ADS valve during the LOCA.

5.2 *Recirculation Line Breaks*

The response during a recirculation line LOCA is dependent on break size. The rate of reactor vessel depressurization decreases as the break size decreases. The high pressure ECCS and ADS will assist in reducing the reactor vessel pressure to the pressure where the LPCI and LPCS flows start. For large breaks, rated LPCS and LPCI flow is generally reached before or shortly after the time when the ADS valves open so the ADS system is not required to mitigate the LOCA. ADS operation is an important emergency system for small breaks where it assists in depressurizing the reactor system faster, and thereby reduces the time required to reach rated LPCS and LPCI flow.

The two largest flow resistances in the recirculation piping are the recirculation pump and the jet pump nozzle. For breaks in the discharge piping, there is a major flow resistance in both flow paths from the reactor vessel to the break. For breaks in the suction piping, the major flow resistances are in the same flow path from the vessel to the break. As a result, pump suction side breaks experience a more rapid blowdown, which tends to make the event more severe. For suction side breaks, the recirculation discharge isolation valve on the broken loop closes which allows the LPCI flow to fill the discharge piping and supply flow to the lower plenum and core. For discharge side breaks, the LPCI flow in the broken loop is assumed to exit the system through the break resulting in a decrease in available LPCI flow to the core, thereby increasing the severity of the event. Both suction and discharge recirculation pipe breaks are considered in the break spectrum analysis.

Two break types (geometries) are considered for the recirculation line break. The two types are the double-ended guillotine (DEG) break and the split break.

For a DEG break, the piping is assumed to be completely severed resulting in two independent flow paths to the containment. The DEG break is modeled by setting the break area (at both ends of the pipe) equal to the full pipe cross-sectional area and varying the discharge coefficient between 1.0 and 0.4. The range of discharge coefficients is used to cover uncertainty in the actual geometry at the break. Discharge coefficients below 0.4 are unrealistic and not considered in the EXEM BWR-2000 methodology. The most limiting DEG break is determined by varying the discharge coefficient.

A split type break is assumed to be a longitudinal opening or hole in the piping that results in a single break flow path to the containment. Appendix K of 10 CFR 50 defines the cross-sectional area of the piping as the maximum split break area required for analysis.

Break types, break sizes and single failures are analyzed for both suction and discharge recirculation line breaks.

Section 6.0 provides a description and results summary for breaks in the recirculation line.

5.3 *Non-Recirculation Line Breaks*

In addition to breaks in the recirculation line, breaks in other reactor coolant system piping must be considered in the LOCA break spectrum analysis. Although the recirculation line large breaks result in the largest coolant inventory loss, they do not necessarily result in the most severe challenge to event acceptance criteria. The double-ended rupture of a main steam line is expected to result in the fastest depressurization of the reactor vessel. Special consideration is required when the postulated break occurs in ECCS piping. Although ECCS piping breaks are small relative to a recirculation pipe DEG break, the potential to disable an ECCS system increases their severity.

The following sections address potential LOCAs due to breaks in non-recirculation line piping.

Non-recirculation line breaks outside of the containment are inherently less challenging to fuel limits than breaks inside the containment. For breaks outside containment, isolation or check valve closure will terminate break flow prior to the loss of significant liquid inventory and the core will remain covered. If high-pressure coolant inventory makeup cannot be reestablished, ADS actuation may become necessary. [

] Although analyses of breaks outside containment may be required to address non-fuel related regulatory requirements, these breaks are not limiting relative to fuel acceptance criteria such as PCT.

5.3.1 Main Steam Line Breaks

A steam line break inside containment is assumed to occur between the reactor vessel and the inboard main steam line isolation valve (MSIV) upstream of the flow limiters. The break results in high steam flow out of the broken line and into the containment. Prior to MSIV closure, a steam line break also results in high steam flow in the intact steam lines as they feed the break via the steam line manifold. A steam line break inside containment results in a rapid depressurization of the reactor vessel. Initially the break flow will be high quality steam; however, the rapid depressurization produces a water level swell that results in liquid discharge at the break. For steam line breaks, the largest break size is most limiting because it results in the most level swell and liquid loss out of the break.

[

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5.3.2 Feedwater Line Breaks

[

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5.3.3 HPCI Line Breaks

The HPCI injection line is connected to the feedwater line outside of the containment.

[

]

The HPCI steam supply line is connected to the main steam line inside of containment.

[

]

5.3.4 LPCS Line Breaks

A break in the LPCS line is expected to have many characteristics similar to [ ] However, some characteristics of the LPCS line break are unique and are not addressed in other LOCA analyses. Two important differences from other LOCA analyses are that the break flow will exit from the region inside the core shroud and the break will disable one LPCS system. The LPCS line break is assumed to occur just outside the reactor vessel. [

]

5.3.5 LPCI Line Breaks

The LPCI injection lines are connected to the larger recirculation discharge lines. [ ]

5.3.6 RWCU Line Breaks

The RWCU extraction line is connected to a recirculation suction line with an additional connection to the vessel bottom head. [

]

The RWCU return line is connected to the feedwater line; [

]

5.3.7 Shutdown Cooling Line Breaks

The shutdown cooling suction piping is connected to a recirculation suction line and the shutdown cooling return line is connected to a recirculation discharge line. [

]

5.3.8 Instrument Line Breaks

[

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Table 5.1 Available ECCS for Recirculation Line Break LOCAs

Assumed Failure *	Recirculation Suction Break	Recirculation Discharge Break
	Systems Remaining †, ‡, §	Systems Remaining ‡, §
DC power (i) (SF-BATT)	1LPCS + 3LPCI + ADS	1LPCS + 1LPCI + ADS
DC power (j)	2 LPCS + 2LPCI + HPCI + ADS	2LPCS + HPCI + ADS
Diesel generator (i)	1LPCS + 3LPCI + HPCI + ADS	1LPCS + 1LPCI + HPCI + ADS
Diesel generator (j)	2LPCS + 2LPCI + HPCI + ADS	2LPCS + HPCI + ADS
LPCI injection valve (SF-LPCI)	2LPCS + 2LPCI + HPCI + ADS	2LPCS + HPCI + ADS
HPCI system (SF-HPCI)	2LPCS + 4LPCI + ADS	2LPCS + 2LPCI + ADS

* Failure of either DC power (i) or diesel generator (i) will result in the loss of one diesel generator (DG-1 or DG-2). The loss of DC power (i) will also result in the loss of the HPCI. The loss of DC power (j) or diesel generator (j) will result in the loss of one diesel generator (DG-3 or DG-4).

† Systems remaining, as identified in this table for recirculation suction line breaks, are applicable to other non-ECCS line breaks. For a LOCA from an ECCS line break, the systems remaining are those listed for recirculation suction breaks, less the ECCS in which the break is assumed.

‡ 1LPCI (1 pump into 1 loop) means one RHR pump operating in one LPCI loop, 2LPCI (2 pumps into 1 loop) means two RHR pumps operating in one loop, 3LPCI (3 pumps into 2 loops) means three RHR pumps operating in two loops, 4LPCI (4 pumps into 2 loops) means four RHR pumps operating in two loops.

§ Although HPCI is expected to be available for some events, no accident analysis mitigation credit is assumed for this system.

6.0 Recirculation Line Break LOCA Analyses

The largest diameter recirculation system pipes are the suction line between the reactor vessel and the recirculation pump and the discharge line between the recirculation pump and the riser manifold ring. LOCA analyses are performed for breaks in both of these locations with consideration for both DEG and split break geometries. The break sizes considered included DEG breaks with discharge coefficients from 1.0 to 0.4 and split breaks with areas ranging between the full pipe area and 0.05 ft^2. As discussed in Section 5.0, the single failures considered in the recirculation line break analyses are SF-BATT and SF-LPCI.

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6.1 *Limiting Break Analysis Results*

The analyses demonstrate that the limiting (highest PCT) recirculation line break is the 0.8 DEG break in the pump discharge piping with an SF-LPCI single failure and a top-peaked axial power shape when operating at 102% rated core power and [ ] The PCT is 1923°F. The key results and event times for this limiting break are provided in Tables 6.1 and 6.2, respectively. Figures 6.1 – 6.25 provide plots of key parameters from the RELAX system and hot channel analyses. A plot of cladding temperature versus time in the hot assembly from the HUXY heatup analysis is provided in Figure 6.26.

Tables 6.3 – 6.6 present the detailed break spectrum PCT results for each of the single failures and state points considered in this LOCA analyses. Table 6.7 provides a summary of the highest PCT recirculation line break calculations for each of the single failures, state points, and axial power shapes. The results of the break analyses are discussed in the following sections.

6.2 *Break Location Analysis Results*

Table 6.7 shows that the maximum PCT calculated for a recirculation line break occurs in the pump discharge piping.

6.3 *Break Geometry and Size Analysis Results*

Recirculation line break PCT results versus break geometry (DEG or split) and size are presented in Tables 6.3 – 6.6. The maximum PCT calculated for a recirculation line break occurs for a 0.8 DEG break.

6.4 *Limiting Single-Failure Analysis Results*

The results in Table 6.7 show that the limiting single-failure is SF-LPCI.

6.5 *Axial Power Shape Analysis Results*

The results in Table 6.7 show that the top-peaked axial power shape is limiting compared to the mid-peaked shape analyses for the limiting break size.

6.6 *State Point Analysis*

Table 6.7 shows that 102% rated core power and [ ] was the limiting state point for the recirculation line breaks.

**Table 6.1 Results for
Limiting TLO Recirculation Line Break
0.8 DEG Pump Discharge SF-LPCI
Top-Peaked Axial 102% Power [ ]**

PCT	1923°F
Maximum local MWR	1.24%
Maximum planar average MWR	0.50%

**Table 6.2 Event Times for
Limiting TLO Recirculation Line Break
0.8 DEG Pump Discharge SF-LPCI
Top-Peaked Axial 102% Power [ ]**

Event	Time (sec)
Initiate break	0.0
Initiate scram	0.6
Low-low liquid level, L2 (459 in)	5.5
Low-low-low liquid level, L1 (358 in)	8.2
Jet pump uncovers	9.4
Recirculation suction uncovers	16.9
Lower plenum flashes	16.1
Diesel generators started	15.0
LPCS high-pressure cutoff	59.8
Power at LPCS injection valves	27.8
LPCS valve pressure permissive	48.0
LPCS valve starts to open	49.0
LPCS valve open	63.0
LPCS pump at rated speed	39.7
LPCS flow starts	63.0
LPCS permissive for ADS	39.7
RDIV pressure permissive	56.5
RDIV starts to close	57.5
RDIV closed	94.5
Rated LPCS flow	87.7
Blowdown ends	87.7
ADS valves open	129.2
Bypass reflood	163.8
Core reflood	174.8
PCT	174.8

Table 6.3 TLO Recirculation Line Break Spectrum Results for [ ] SF-BATT

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Table 6.4 TLO Recirculation Line Break Spectrum Results for [ ] SF-LPCI

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Table 6.5 TLO Recirculation Line Break Spectrum Results for [ ] Flow SF-BATT

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Table 6.6 TLO Recirculation Line Break Spectrum Results for [ ] Flow SF-LPCI

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**Table 6.7 Summary of TLO Recirculation Line Break Results
Highest PCT Cases**

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**Figure 6.1 Limiting TLO Recirculation Line Break
Upper Plenum Pressure**

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**Figure 6.2 Limiting TLO Recirculation Line Break
Total Break Flow Rate**

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Figure 6.3 Limiting TLO Recirculation Line Break Core Inlet Flow Rate

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Figure 6.4 Limiting TLO Recirculation Line Break Core Outlet Flow Rate

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Figure 6.5 Limiting TLO Recirculation Line Break Intact Loop Jet Pump Drive Flow Rate

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Figure 6.6 Limiting TLO Recirculation Line Break Intact Loop Jet Pump Suction Flow Rate

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Figure 6.7 Limiting TLO Recirculation Line Break Intact Loop Jet Pump Exit Flow Rate

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Figure 6.8 Limiting TLO Recirculation Line Break Broken Loop Jet Pump Drive Flow Rate

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Figure 6.9 Limiting TLO Recirculation Line Break Broken Loop Jet Pump Suction Flow Rate

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Figure 6.10 Limiting TLO Recirculation Line Break Broken Loop Jet Pump Exit Flow Rate

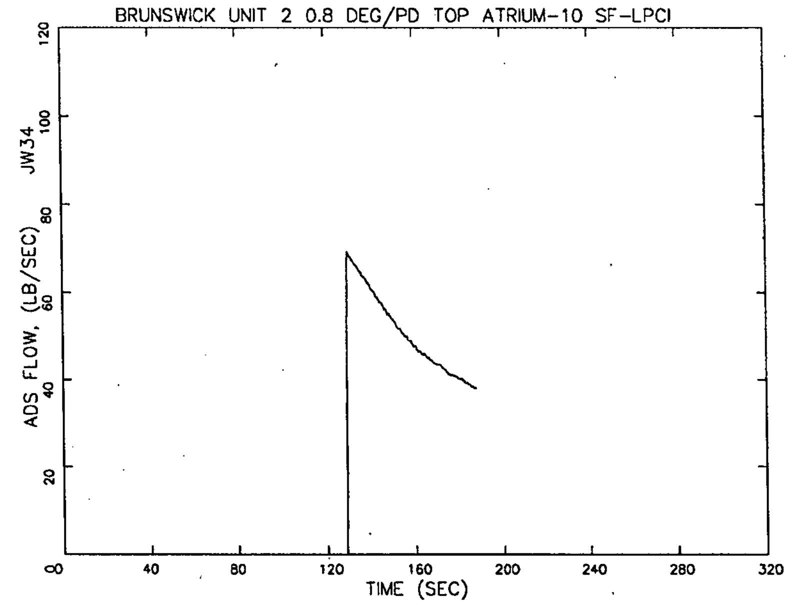

Figure 6.11 Limiting TLO Recirculation Line Break ADS Flow Rate

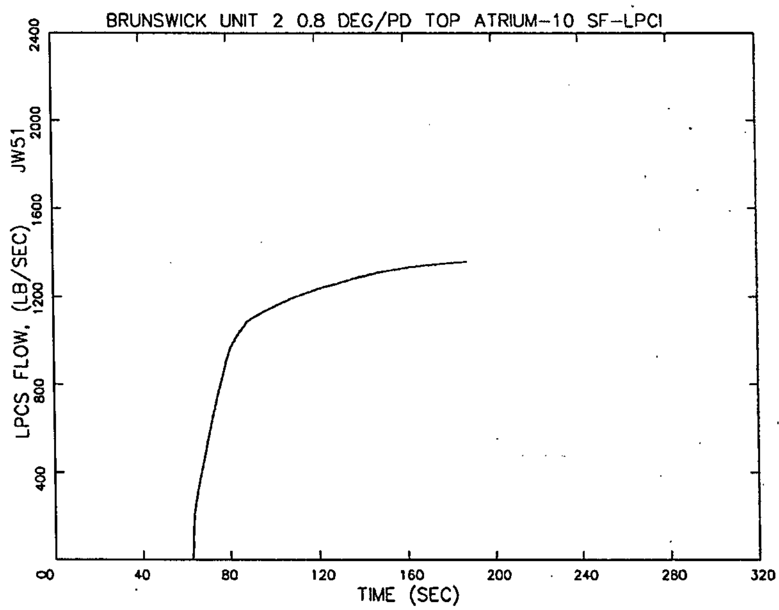

Figure 6.12 Limiting TLO Recirculation Line Break LPCS Flow Rate

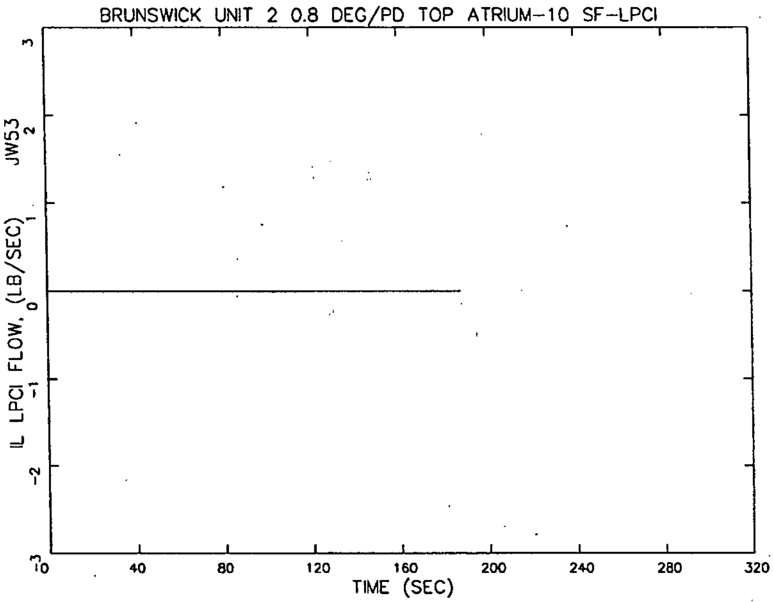

Figure 6.13 Limiting TLO Recirculation Line Break Intact Loop LPCI Flow Rate

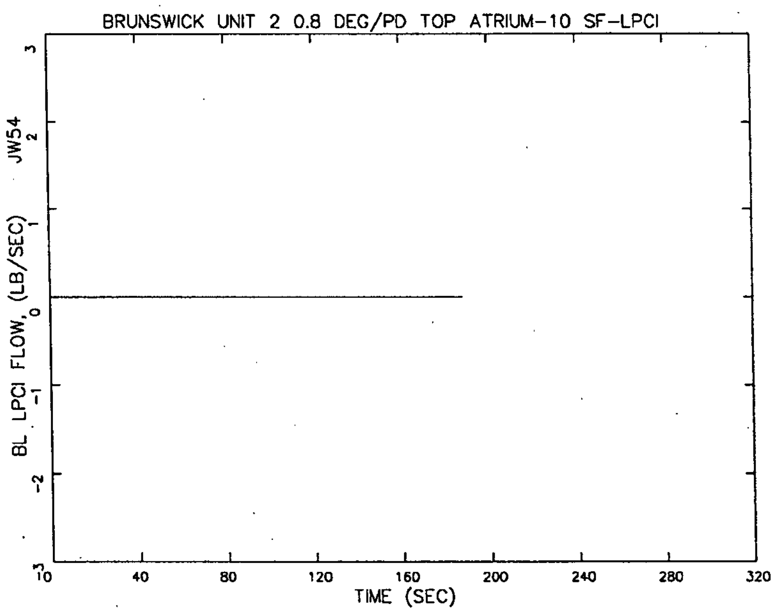

Figure 6.14 Limiting TLO Recirculation Line Break Broken Loop LPCI Flow Rate

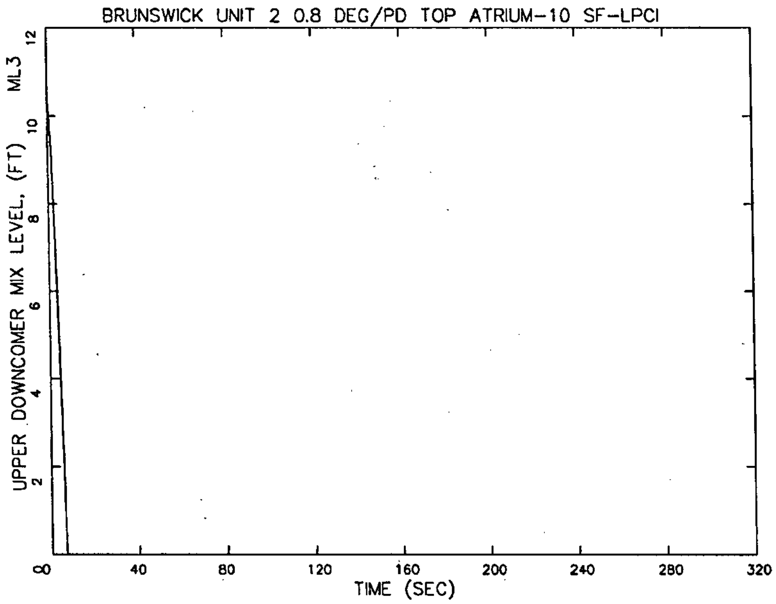

Figure 6.15 Limiting TLO Recirculation Line Break Upper Downcomer Mixture Level

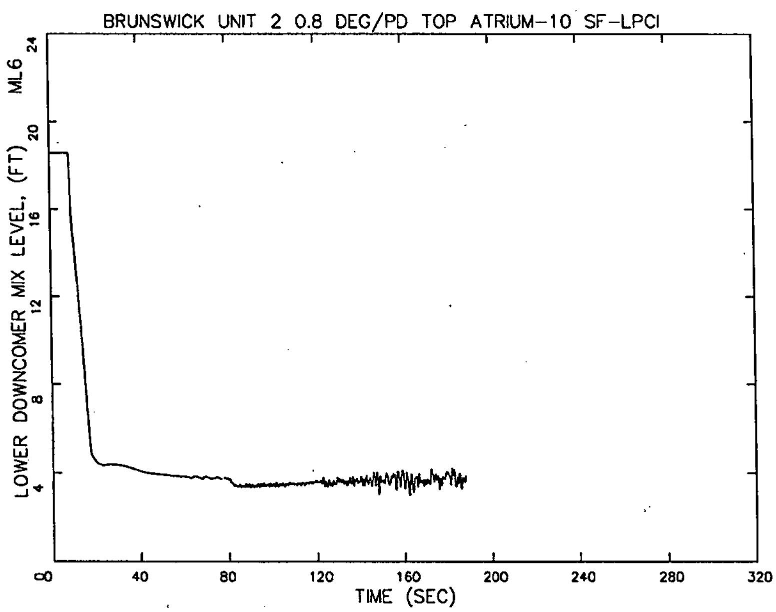

Figure 6.16 Limiting TLO Recirculation Line Break Lower Downcomer Mixture Level

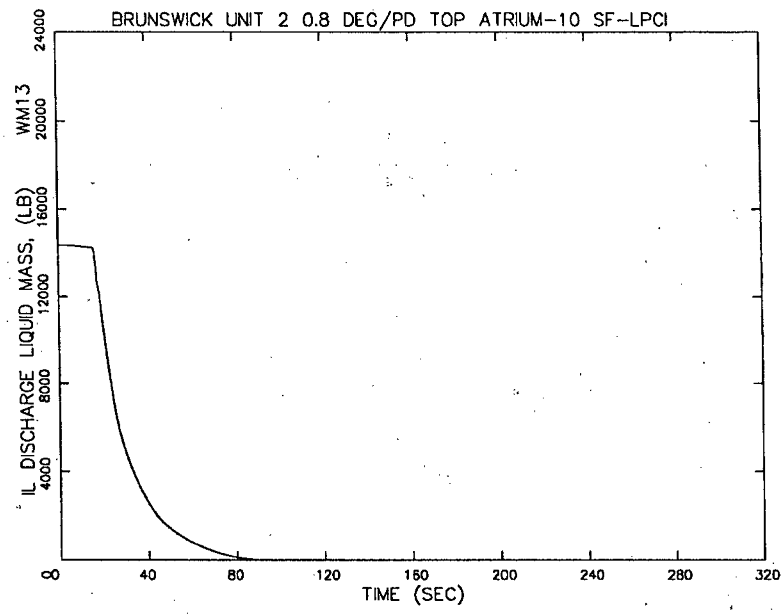

Figure 6.17 Limiting TLO Recirculation Line Break Intact Loop Discharge Line Liquid Mass

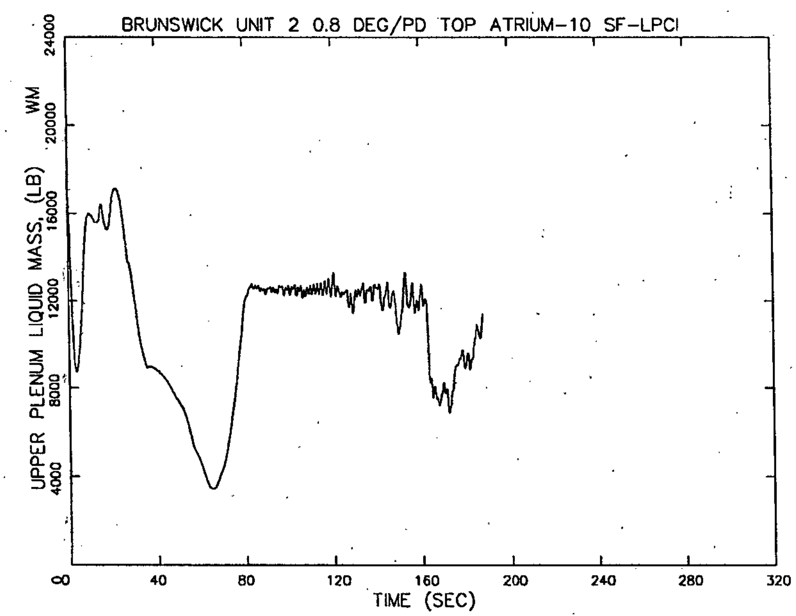

Figure 6.18 Limiting TLO Recirculation Line Break Upper Plenum Liquid Mass

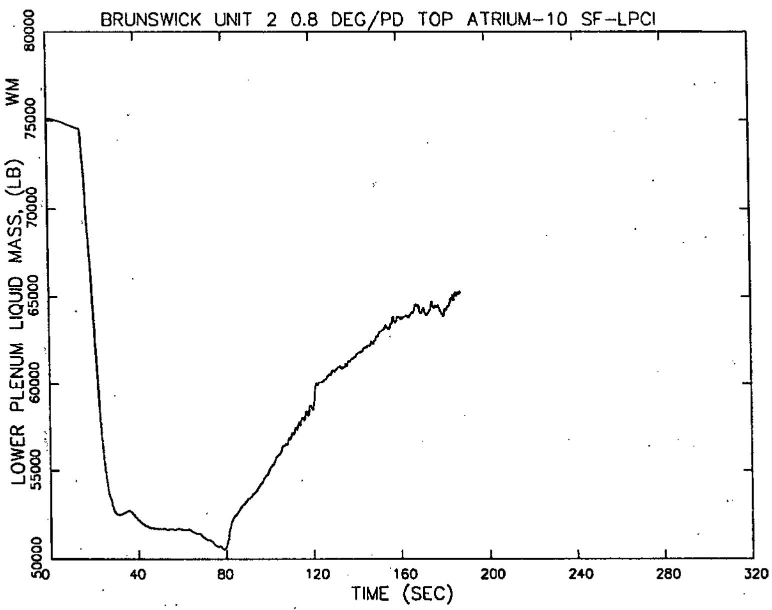

Figure 6.19 Limiting TLO Recirculation Line Break Lower Plenum Liquid Mass

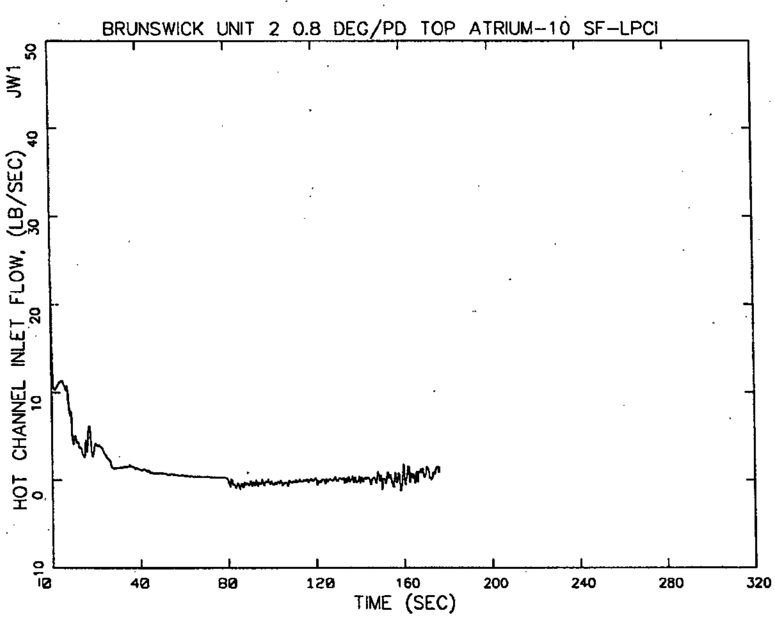

Figure 6.20 Limiting TLO Recirculation Line Break Hot Channel Inlet Flow Rate

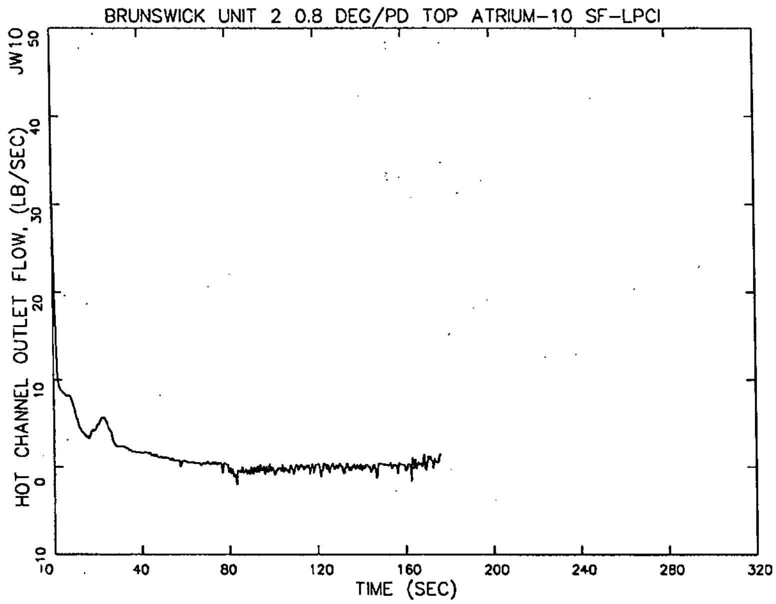

**Figure 6.21 Limiting TLO Recirculation Line Break
Hot Channel Outlet Flow Rate**

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**Figure 6.22 Limiting TLO Recirculation Line Break
Hot Channel Coolant Temperature at the Hot Node at EOB**

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**Figure 6.23 Limiting TLO Recirculation Line Break
Hot Channel Quality at the Hot Node at EOB**

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**Figure 6.24 Limiting TLO Recirculation Line Break
Hot Channel Heat Transfer Coeff. at the Hot Node at EOB**

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**Figure 6.25 Limiting TLO Recirculation Line Break
Hot Channel Reflood Junction Liquid Mass Flow Rate**

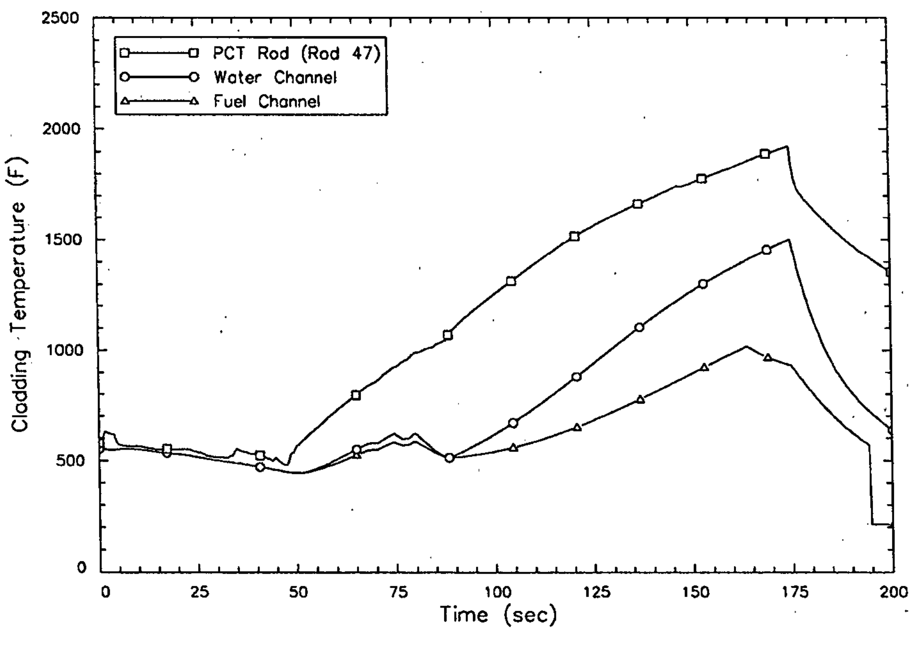

**Figure 6.26 Limiting TLO Recirculation Line Break
Cladding Temperatures**

7.0 Single-Loop Operation LOCA Analysis

During SLO the pump in one recirculation loop is not operating. A break may occur in either loop, but results from a break in the inactive loop would be similar to those from a two-loop operation break. If a break occurs in the inactive loop during SLO, the intact active loop flow to the reactor vessel would continue during the recirculation pump coastdown period and would provide core cooling similar to that which would occur in breaks during TLO. System response would be similar to that resulting from an equal-sized break during two-loop operation. A break in the active loop during SLO results in a more rapid loss of core flow and earlier degraded core conditions relative to those from a break in the inactive loop. Therefore, only breaks in the active recirculation loop are analyzed.

A break in the active recirculation loop during SLO will result in an earlier loss of core heat transfer relative to a similar break occurring during two-loop operation. This occurs because there will be an immediate loss of jet pump drive flow. Therefore, fuel rod surface temperatures will increase faster in an SLO LOCA relative to a TLO LOCA. Also, the early loss of core heat transfer will result in higher stored energy in the fuel rods at the start of the heatup. The increased severity of an SLO LOCA can be reduced by applying an SLO multiplier to the two-loop MAPLHGR limits. [

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7.1 *SLO Analysis Modeling Methodology*

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7.2 *SLO Analysis Results*

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The SLO analyses are performed with a 0.85 multiplier applied to the two-loop MAPLHGR limit resulting in an SLO MAPLHGR limit of 10.625 kW/ft. The analyses are performed at BOL fuel conditions. The limiting SLO LOCA is the 1.0 DEG pump discharge line break with SF-LPCI and a top-peaked axial power shape. The PCT for this case is 1865°F. Other key results and event times for the limiting SLO LOCA are provided in Tables 7.1 and 7.2, respectively. Figures 7.1 – 7.25 show important RELAX system and hot channel results from the SLO limiting LOCA analysis. Figure 7.26 shows the cladding surface temperature for the limiting rod as calculated by HUXY.

Table 7.3 shows the spectrum of SLO analyses and the PCT for each case. A comparison of the limiting SLO and the limiting two-loop results is provided in Table 7.4. The results in Table 7.4 show that the limiting two-loop LOCA results bound the limiting SLO results when a 0.85 multiplier is applied to the two-loop MAPLHGR limit.

**Table 7.1 Results for
Limiting SLO Recirculation Line Break
1.0 DEG Pump Discharge SF-LPCI
Top-Peaked Axial [ ]**

PCT	1865°F
Maximum local MWR	1.10%
Maximum planar average MWR	0.49%

**Table 7.2 Event Times for
Limiting SLO Recirculation Line Break
1.0 DEG Pump Discharge SF-LPCI
Top-Peaked Axial [ ]**

Event	Time (sec)
Initiate break	0.0
Initiate scram	0.6
Low-Low liquid level, L2 (459 in)	5.7
Low-Low-Low liquid level, L1 (358 in)	8.5
Jet pump uncovers	9.9
Recirculation suction uncovers	17.6
Lower plenum flashes	16.4
Diesel generators started	15.0
LPCS high-pressure cutoff	59.5
Power at LPCS injection valves	27.8
LPCS valve pressure permissive	47.7
LPCS valve starts to open	48.7
LPCS valve open	62.7
LPCS pump at rated speed	39.7
LPCS flow starts	62.8
LPCS permissive for ADS	39.7
RDIV pressure permissive	56.3
RDIV starts to close	57.3
RDIV closed	94.3
Rated LPCS flow	86.9
Blowdown ends	86.9
ADS valves open	129.5
Bypass reflood	131.9
Core reflood	175.0
PCT	175.0

Table 7.3 SLO Recirculation Line Break Spectrum Results

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Table 7.4 Single- and Two-Loop Operation PCT Summary

Operation	Limiting Case	PCT (°F)
Single-loop	1.0 DEG pump discharge top-peaked SF-LPCI	1865
Two-loop	0.8 DEG pump discharge top-peaked SF-LPCI	1923

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**Figure 7.1 Limiting SLO Recirculation Line Break
Upper Plenum Pressure**

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**Figure 7.2 Limiting SLO Recirculation Line Break
Total Break Flow Rate**

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**Figure 7.3 Limiting SLO Recirculation Line Break
Core Inlet Flow Rate**

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**Figure 7.4 Limiting SLO Recirculation Line Break
Core Outlet Flow Rate**

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Figure 7.5 Limiting SLO Recirculation Line Break Intact Loop Jet Pump Drive Flow Rate

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Figure 7.6 Limiting SLO Recirculation Line Break Intact Loop Jet Pump Suction Flow Rate

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**Figure 7.7 Limiting SLO Recirculation Line Break
Intact Loop Jet Pump Exit Flow Rate**

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**Figure 7.8 Limiting SLO Recirculation Line Break
Broken Loop Jet Pump Drive Flow Rate**

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Figure 7.9 Limiting SLO Recirculation Line Break Broken Loop Jet Pump Suction Flow Rate

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Figure 7.10 Limiting SLO Recirculation Line Break Broken Loop Jet Pump Exit Flow Rate

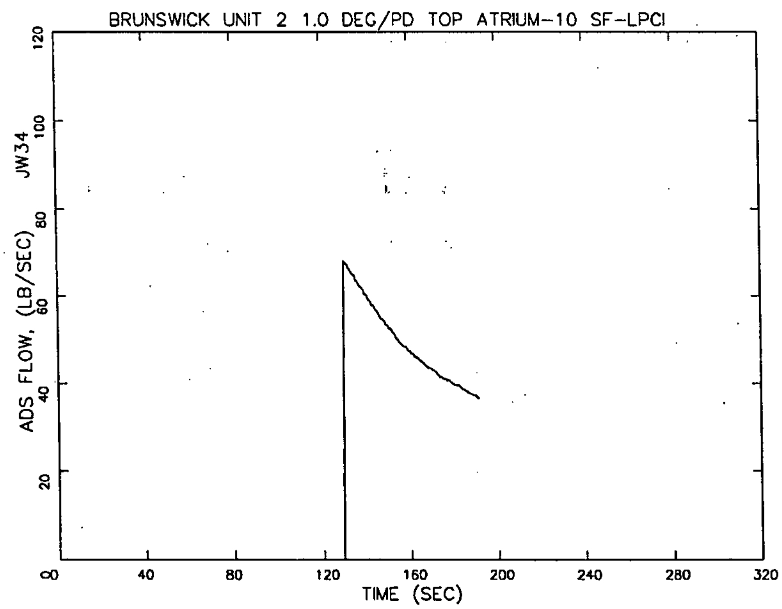

Figure 7.11 Limiting SLO Recirculation Line Break ADS Flow Rate

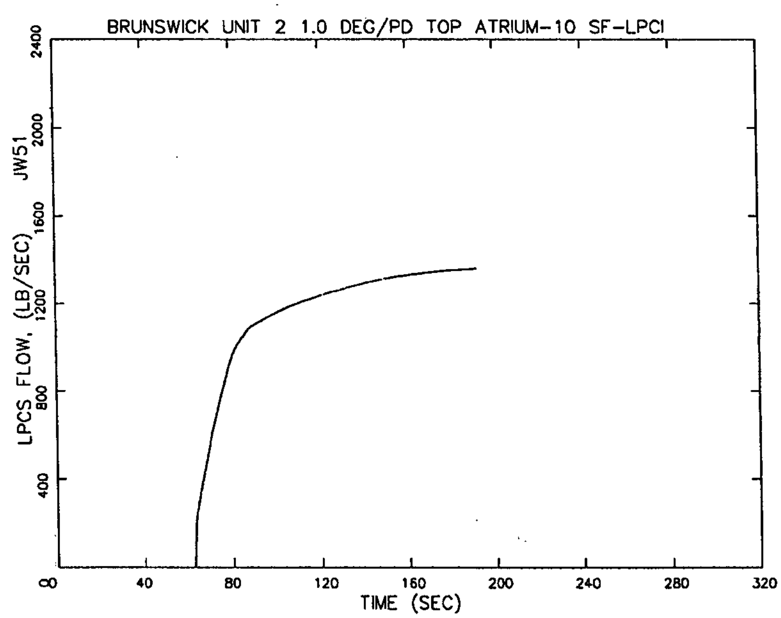

Figure 7.12 Limiting SLO Recirculation Line Break LPCS Flow Rate

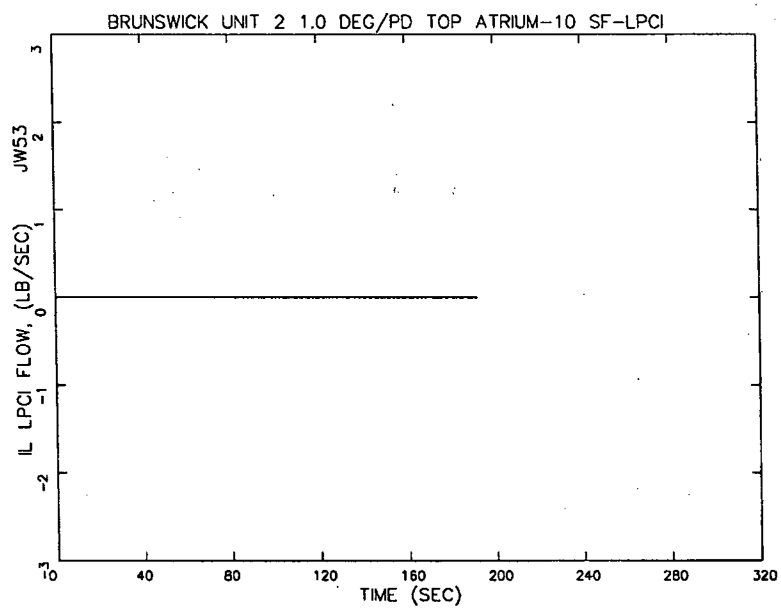

Figure 7.13 Limiting SLO Recirculation Line Break Intact Loop LPCI Flow Rate

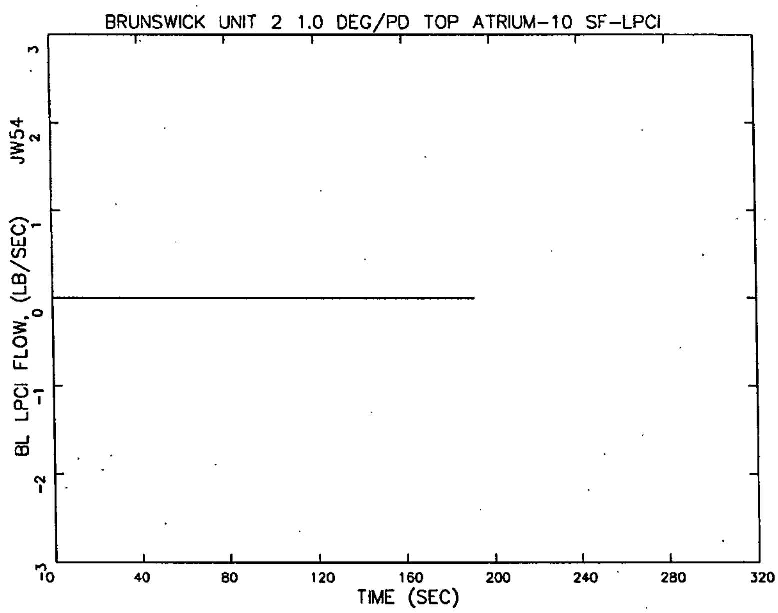

Figure 7.14 Limiting SLO Recirculation Line Break Broken Loop LPCI Flow Rate

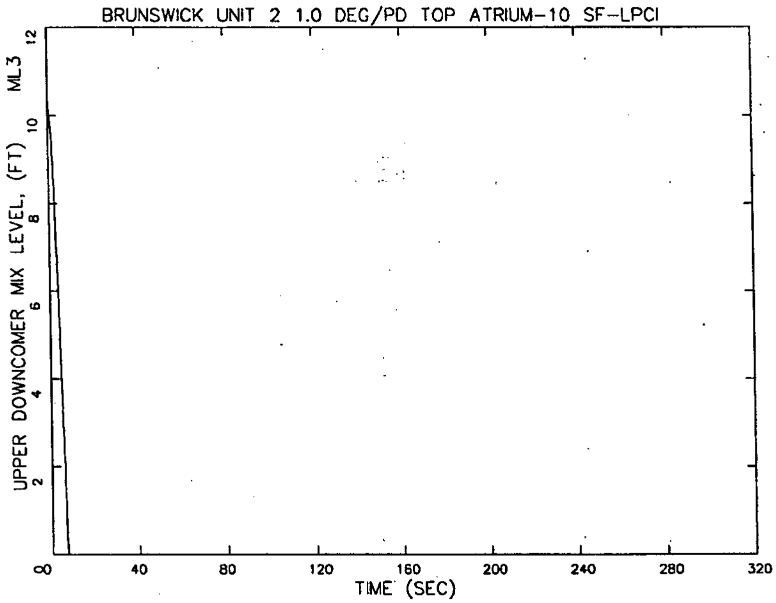

Figure 7.15 Limiting SLO Recirculation Line Break Upper Downcomer Mixture Level

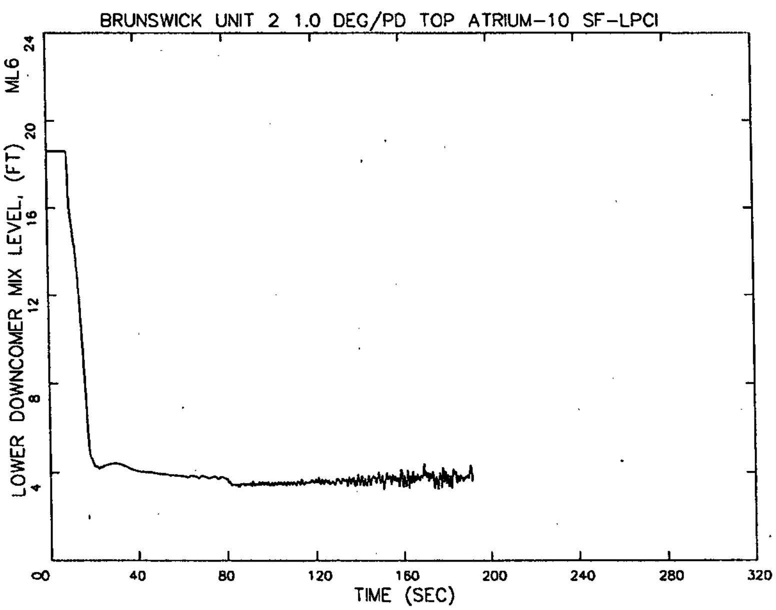

Figure 7.16 Limiting SLO Recirculation Line Break Lower Downcomer Mixture Level

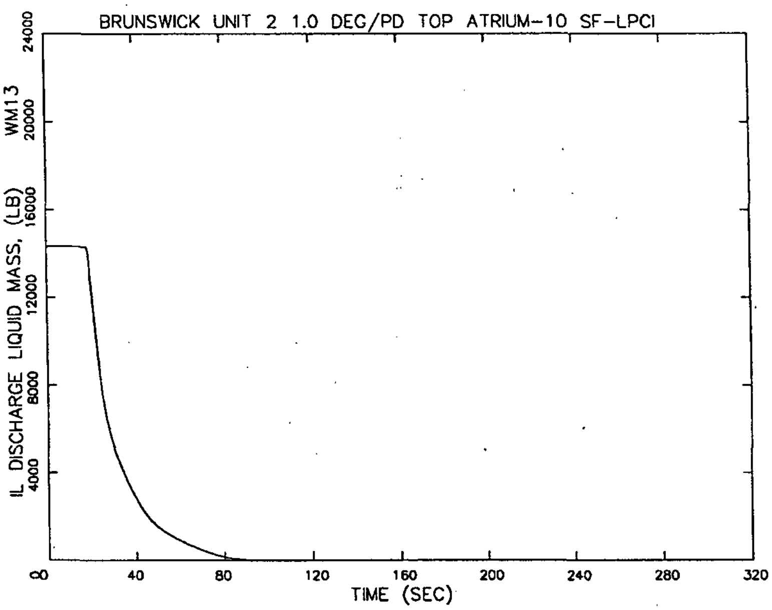

Figure 7.17 Limiting SLO Recirculation Line Break Intact Loop Discharge Line Liquid Mass

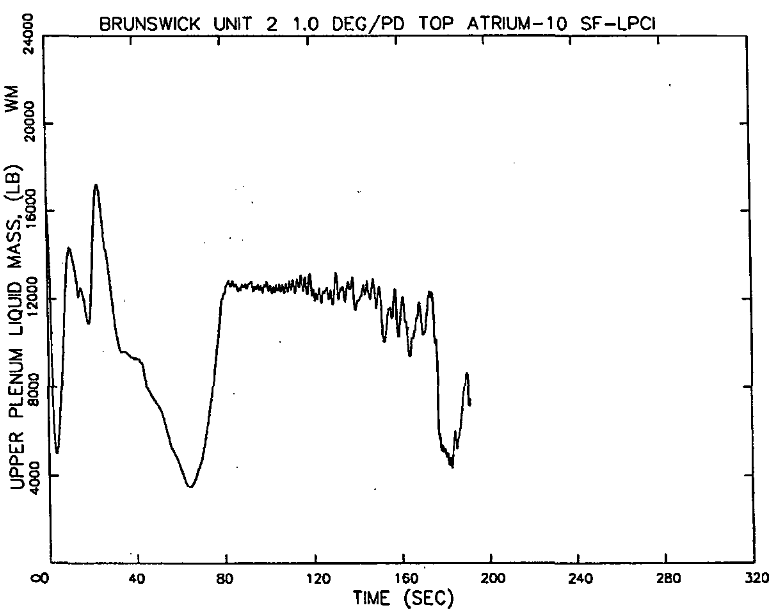

Figure 7.18 Limiting SLO Recirculation Line Break Upper Plenum Liquid Mass

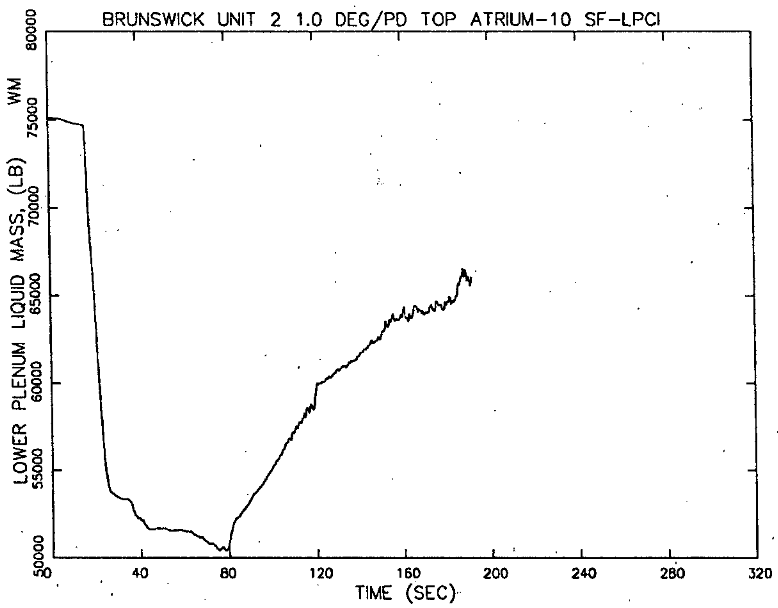

Figure 7.19 Limiting SLO Recirculation Line Break Lower Plenum Liquid Mass

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Figure 7.20 Limiting SLO Recirculation Line Break Hot Channel Inlet Flow Rate

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**Figure 7.21 Limiting SLO Recirculation Line Break
Hot Channel Outlet Flow Rate**

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**Figure 7.22 Limiting SLO Recirculation Line Break
Hot Channel Coolant Temperature at the Hot Node at EOB**

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Figure 7.23 Limiting SLO Recirculation Line Break
Hot Channel Quality at the Hot Node at EOB

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Figure 7.24 Limiting SLO Recirculation Line Break
Hot Channel Heat Transfer Coeff. at the Hot Node at EOB

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**Figure 7.25 Limiting SLO Recirculation Line Break
Hot Channel Reflood Junction Liquid Mass Flow Rate**

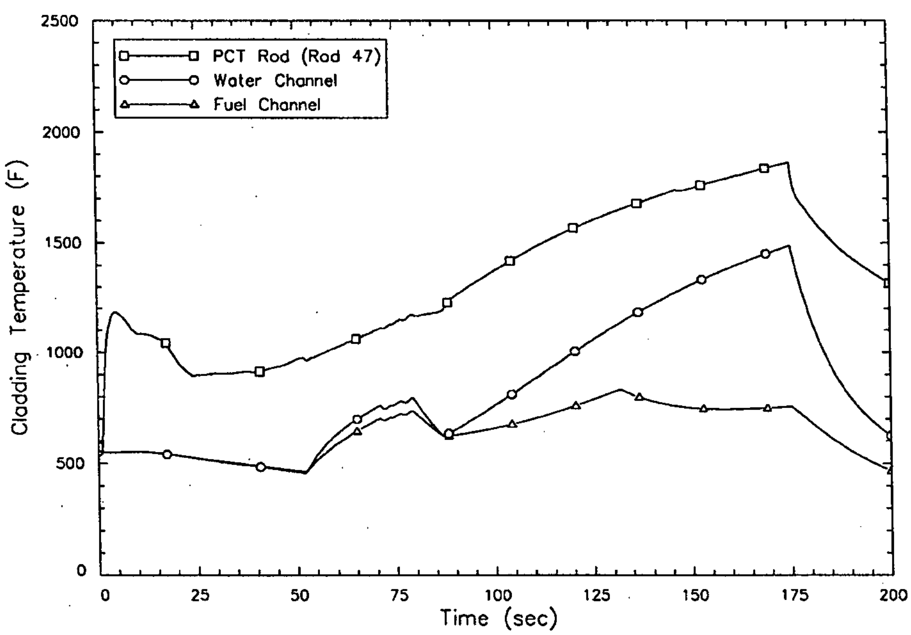

**Figure 7.26 Limiting SLO Recirculation Line Break
Cladding Temperatures**

8.0 Long-Term Coolability

Long-term coolability addresses the issue of reflooding the core and maintaining a water level adequate to cool the core and remove decay heat for an extended time period following a LOCA. For non-recirculation line breaks, the core can be reflooded to the top of the active fuel and be adequately cooled indefinitely. For recirculation line breaks, the core will initially remain covered following reflood due to the static head provided by the water filling the jet pumps to a level of approximately two-thirds core height. Eventually, the heat flux in the core will not be adequate to maintain a two-phase water level over the entire length of the core. Beyond this time, the upper third of the core will remain wetted and adequately cooled by core spray. Maintaining water level at two-thirds core height with one core spray system operating is sufficient to maintain long-term coolability as demonstrated by the NSSS vendor (Reference 7). Since fuel temperatures during long-term cooling are low relative to the PCT and are not significantly affected by fuel design, this conclusion is applicable to ATRIUM-10 fuel.

9.0 Conclusions

The major conclusions of this LOCA break spectrum analysis are:

- The limiting recirculation line break is a 0.8 DEG break in the pump discharge piping with single failure SF-LPCI and a top-peaked axial shape when operating at 102% rated core power and [ ]
- The limiting break analysis identified above satisfies all of the acceptance criteria specified in 10 CFR 50.46. The analysis is performed in accordance with 10 CFR 50.46 Appendix K requirements.
- The MAPLHGR limit multiplier for SLO is 0.85 for ATRIUM-10 fuel. This multiplier ensures that a LOCA from SLO is less limiting than a LOCA from two-loop operation.

The limiting break characteristics determined in this report can be referenced and used in future Brunswick Units 1 and 2 LOCA analyses to establish the MAPLHGR limit versus exposure for ATRIUM-10 fuel.

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1. EMF-2361(P)(A) Revision 0, *EXEM BWR-2000 ECCS Evaluation Model*, Framatome ANP, May 2001.

2. XN-CC-33(P)(A) Revision 1, *HUXY: A Generalized Multirod Heatup Code with 10 CFR 50 Appendix K Heatup Option Users Manual*, Exxon Nuclear Company, November 1975.

3. XN-NF-82-07(P)(A) Revision 1, *Exxon Nuclear Company ECCS Cladding Swelling and Rupture Model*, Exxon Nuclear Company, November 1982.

4. XN-NF-81-58(P)(A) Revision 2 and Supplements 1 and 2, *RODEX2 Fuel Rod Thermal-Mechanical Response Evaluation Model*, Exxon Nuclear Company, March 1984.

5. EMF-2292(P)(A) Revision 0, *ATRIUM-10: Appendix K Spray Heat Transfer Coefficients*, Siemens Power Corporation, September 2000.

6. *Updated FSAR Brunswick Steam Electric Plant, Units 1 and 2*, Revision 20.

7. NEDO-20566A, *General Electric Company Analytical Model for Loss of Coolant Analysis in Accordance with 10CFR50 Appendix K*, September 1986.